THE WEATHER AND CIRCULATION OF JUNE 1957 [1]

Including an Analysis of Hurricane Audrey in Relation to the Mean Circulation

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1. COMPARISON WITH SPRING MONTHS

The weather in the United States during the spring of 1957 was severe in many areas. The prolonged drought of 1952–56 in southern and central parts of the Great Plains [16] was broken by blizzards and heavy rains during both March [4] and April [1]. Intensification of the heavy precipitation during May [3] produced disastrous floods in this region. At the same time, tornado activity, which had been frequent in April, reached peak intensity and made this May the worst tornado month ever experienced in the United States.

In many respects June's weather regime was a continuation of that which had prevailed throughout the spring season. This is well illustrated by figure 1, which shows that the pattern of departure of average temperature from normal during June closely resembled the corresponding average for the months of March, April, and May. Some similarity was also apparent between the maps showing the percentage of normal precipitation for June and for the preceding three months. (See *Weekly Weather and Crop Bulletin, National Summary* for weeks ending June 10 and July 8). During June, tornadoes, heavy rains, and floods in central portions of the United States again made newspaper headlines.

On a month-to-month basis the weather in the United States was also unusually persistent. The striking resemblance between April and May of 1957 was noted in the previous article of this series [3]. Between May and June of this year, only 18 out of 100 stations scattered over the United States had changes of more than one class in their monthly mean temperature anomaly, compared to an average of 30 for the years from 1942 to 1954 [10] and 40 expected by chance. No change in precipitation class was reported by 42 stations, a considerably greater number than the 33 expected both by chance and by the average of previous May–June periods.

Although many features of June's weather were thus quite persistent from the preceding month and season, nevertheless there were some large changes. Most striking, perhaps, was the warming which occurred in the Southwest (fig. 1), where some stations reported a four-class change in temperature, from much below normal during May to much above normal in June. This warming

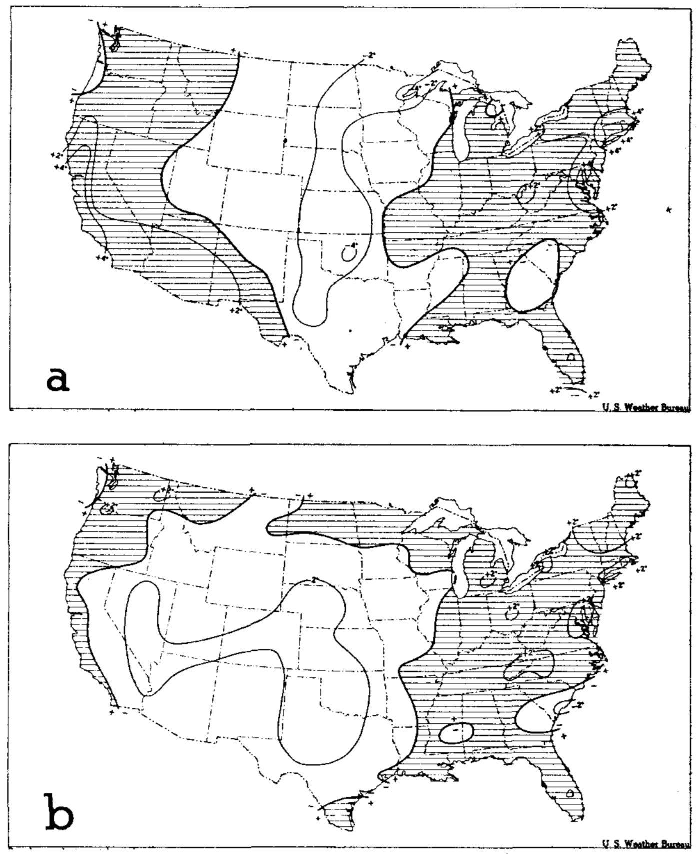

FIGURE 1.—Departure of average surface temperature from normal (° F.) with shaded areas normal or above, for (a) June 1957 and (b) spring 1957 (March, April, May). Similarity in pattern is striking except for warming in the Southwest in June. (From *Weekly Weather and Crop Bulletin, National Summary* for weeks ending June 10 and July 1, 1957.)

was associated in part with an abrupt northward shift of the mean jet stream at the 200-mb. level as illustrated in figure 2, which gives the location of the jet axis computed from a series of monthly mean 200-mb. maps. Whereas the mean jet was located over northern Mexico and southern Texas during the three spring months, it traversed the central Plateau and Northern Plains during June (fig. 3). This shift was probably greater in magnitude than the normal seasonal trend, but normal 200-mb. maps are not available for comparison. At any rate, it was reflected in displacement of the area of worst weather

[1] See Charts I–XVII following p. 228 for analyzed climatological data for the month.

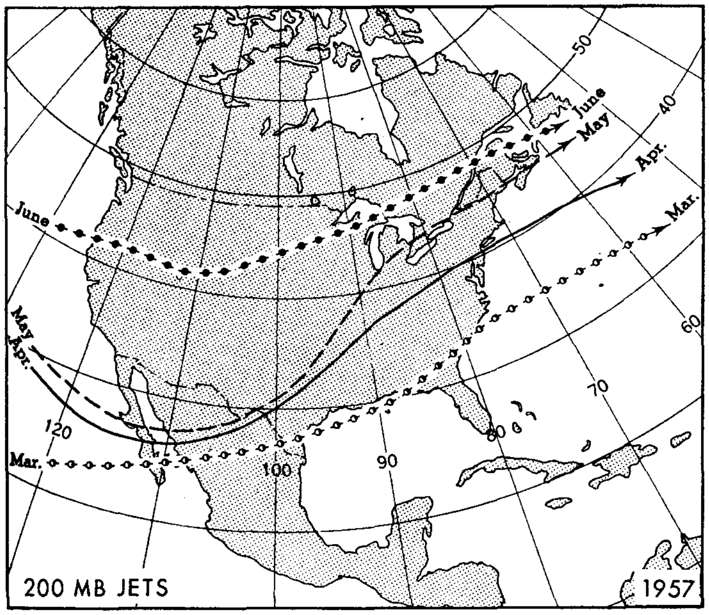

FIGURE 2.—Location of principal axis of mean jet stream during each spring month of 1957, as obtained from monthly mean 200-mb. charts. Gradual northward progression over the 4-month period of the jet in the East contrasted with its abrupt northward shift from May to June in the West.

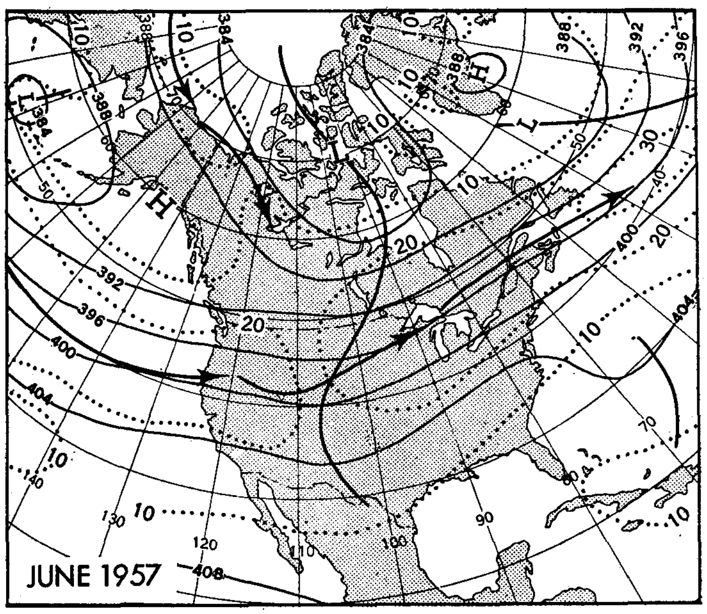

FIGURE 3.—Mean 200-mb. contours (solid, in hundreds of feet) and isotachs (dotted, in meters per second) for June 1957. Solid arrows indicate the position of the 200-mb. mean jet stream. Note split jet around blocking High in Gulf of Alaska, with one branch between 40° N. and 50° N. and the other around 70° N.

(tornadoes and floods) from the Southern Plains during May to northern portions of the Plains and Mississippi Valley in June. The northward shift of the jet stream occurred also in the eastern part of the country, but to a lesser degree and in a more gradual fashion (fig. 2). There too it was accompanied by general surface warming, with parts of the Northeast changing from below normal temperatures in May to above normal in June.

Thus, June 1957 was a transition month in which the weather and circulation pattern of spring was replaced by one more typical of summer. This evolution is examined on a week-to-week basis in section 3, after details of the monthly mean are discussed in section 2. The establishment of a summer regime culminated, during the last week of the month, with the appearance of hurricane Audrey. This storm is analyzed in relation to the mean circulation in section 4.

2. MONTHLY MEAN CIRCULATION AND WEATHER

The general circulation over North America during June 1957 was fairly simple in pattern, consisting of a deep trough through the central part of the continent flanked by ridges along each coast. This pattern is well illustrated by the monthly mean maps at 200 mb. (fig. 3) and 700 mb. (fig. 4), and it was evident at all levels of the atmosphere from sea level (Chart XI) up to 100 mb. (Chart XVII). The northern portion of each ridge was affiliated with a blocking High. These Highs, centered over Greenland and Alaska, respectively, were of the warm type since they extended as closed circulations up to the 200-mb. level. Warmth, relative to its surroundings, was also a feature of the southern portion of the North American trough extending through the western Gulf of Mexico, since a closed Low was present at 700 mb. (fig. 4) but no trough at all at 200 mb. (fig. 3). This trough was made up in part by tropical activity, especially hurricane Audrey (see sec. 4).

The dotted lines in figure 4 show that monthly mean 700-mb. heights were below the June normal throughout the length of the trough from Central America to the Arctic Ocean, with greatest departures (−210 ft.) over northern Manitoba. Conversely, above normal heights prevailed in the mean ridges along the Atlantic and Pacific coasts. The pattern of surface temperature departure from normal for the month was very similar to this, as illustrated in figure 1A and Chart I–B for the United States. As would be expected, however, the axes of above and below normal temperatures were displaced westward (about 5° longitude) relative to the corresponding values for height, with warm air in the southerly flow east of the trough and cool air in the northerly components to its west. Maximum temperature anomalies in the United States were +4° F. in southern New England and western California, where positive 700-mb. height anomalies are centered in figure 1, and −4° F. around Duluth and Oklahoma City.

The mean trough through the central United States was associated with the passage of numerous migratory cyclones (Chart X) and with the influx of considerable moisture from the Gulf of Mexico at low levels. As a result abundant precipitation was widespread throughout the United States (Charts II and III). Rainfall was especially heavy in the region of stronger than normal

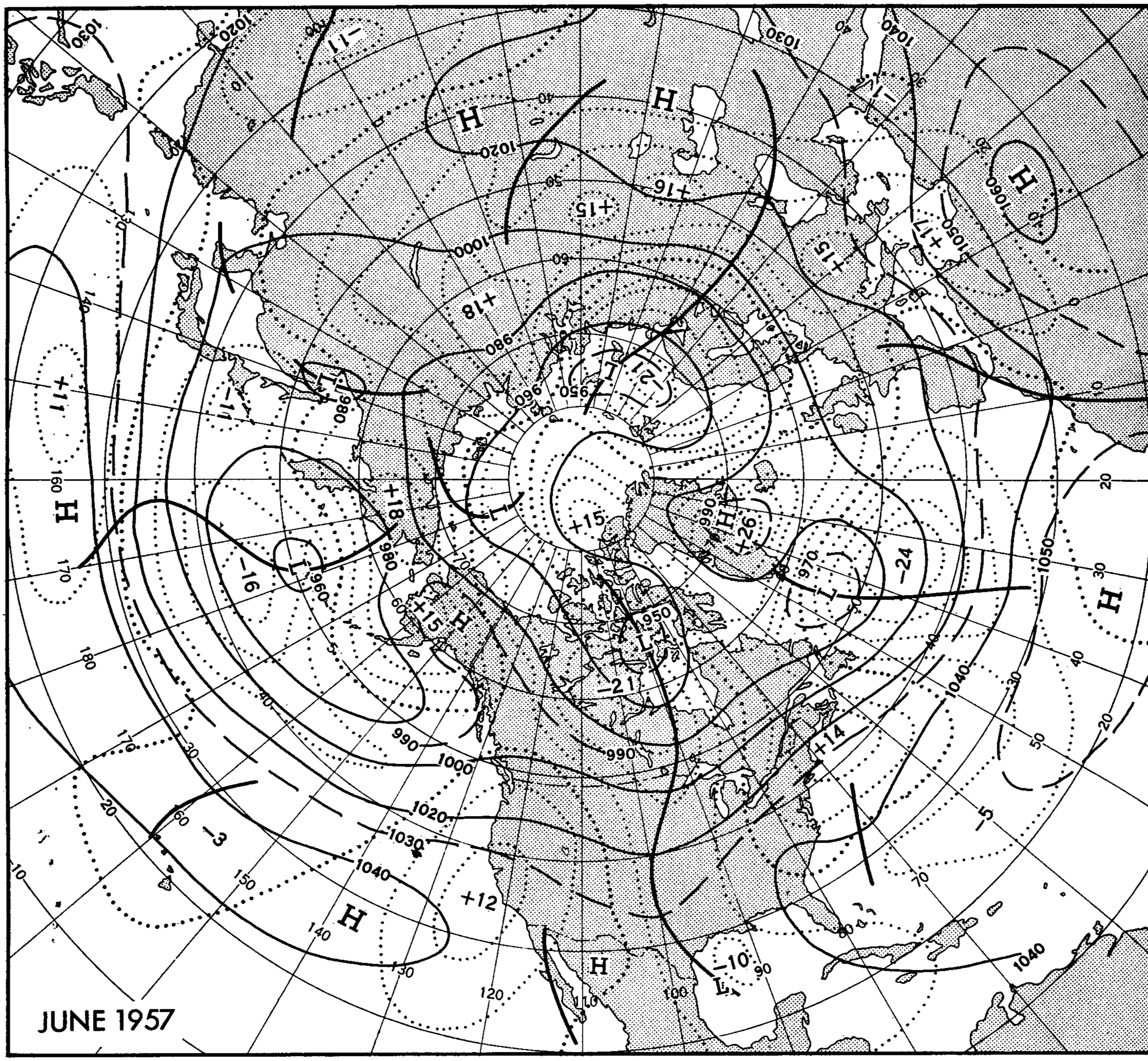

FIGURE 4.—Mean 700-mb. contours (solid) and height departures from monthly normal (dotted) (both in tens of feet) for June 1957. The mean trough (heavy vertical line) through the central United States, where troughs are seldom observed in June, was accompanied by severe weather in many parts of the Great Plains and Mississippi Valley.

southerly winds just east of the trough, and over twice the normal amount fell in portions of the Central Plains, Mississippi Valley, and Great Lakes area. This was in good agreement with the results of an earlier study on the relation between summer rain in this region and monthly mean 700-mb. charts [5]. The intensity and areal extent of this rainfall is indicated by the fact that this was the wettest June on record at Shreveport, La., St. Louis, Mo., Sioux City, Iowa, Fort Wayne, Ind., Youngstown, Ohio, and Erie, Pa.

In contrast to the heavy rains in other parts of the country, the dry weather of April [1] and May [3] continued along the Atlantic seaboard from Virginia northward. This was the third driest June in 84 years at New Haven, Conn., and the second driest at Providence, R. I. At the latter city only 1.58 inches of rain fell from April 10 to June 30, the most prolonged spring drought in 53 years of record. This 3-month dry spell was closely related to the persistence of a mean ridge and its accompanying center of positive height anomaly over the North Atlantic States each month from April through June (see monthly mean 700-mb. charts in fig. 4 and in the previous two articles of this series [1 and 3]). Subsidence prevailed under this ridge, with anticyclonic conditions at sea level (Chart XI), as the Northeast was traversed by numerous migratory Highs (Chart IX) but very few Lows (Chart X).

3. TRANSITION WITHIN THE MONTH

The abrupt northward displacement of the monthly mean jet stream from May to June illustrated in figure 2 was accomplished by an interesting evolution within the month of June. This was investigated by constructing isotachs on a sequence of 5-day mean 200-mb. charts a week apart encompassing the period from June 1 to July 3. The location of the principal jet axis over the United States obtained from each of these maps is illustrated in figure 5. During the first period (June 1–5) the 200-mb. jet stream was split into two branches, with one axis unusually far south over Mexico and the West Indies, and the other along the northern border of the United States. The next week (June 8–12) each of these branches migrated northward, the first to the Southern Plains and the second to southern Canada. By the third period (June 15–19) the two jet axes apparently merged, and a single well-developed jet stream (with geostrophic speeds of 70–80 m. p. h.) curved cyclonically from the Central Plateau across the Northern Plains into southeastern Canada. Its position was very close to that given on the monthly mean 200-mb. map (fig. 3). A week later (June 22–26), little change in intensity or location of the jet occurred, except for some continued northward displacement in the western United States. By the final week (June 29–July 3) a single, intense jet stream stretched across the northern border of the United States. Its anticyclonic curvature in the West and cyclonic curvature in the East was in marked contrast to its orientation during the preceding three weeks.

Thus, in the course of a month, an axis of the jet stream seemed to migrate from the southern to the northern border of the country in the western half of the United States, while in the East initial northward displacement was followed by abrupt southward shift during the final week. The nature and effect of this intramonthly transition will now be discussed in greater detail with the aid of a series of weekly maps depicting 5-day mean 700-mb. heights and their departures from normal (fig. 6), weekly surface temperature anomalies (fig. 7), and total weekly precipitation (fig. 8).

FIRST WEEK

The split in the jet stream during the first two periods given in figure 5 was reflected as a sheared trough at 700 mb. from June 4 to 8 (fig. 6A), with one low center over Texas and another over Labrador. Each of these Lows was associated with an area of below normal heights at 700 mb. (fig. 6A) and below normal temperatures at the surface (fig. 7a). Weekly temperature departures averaged as much as −6° F. in central Texas and in parts

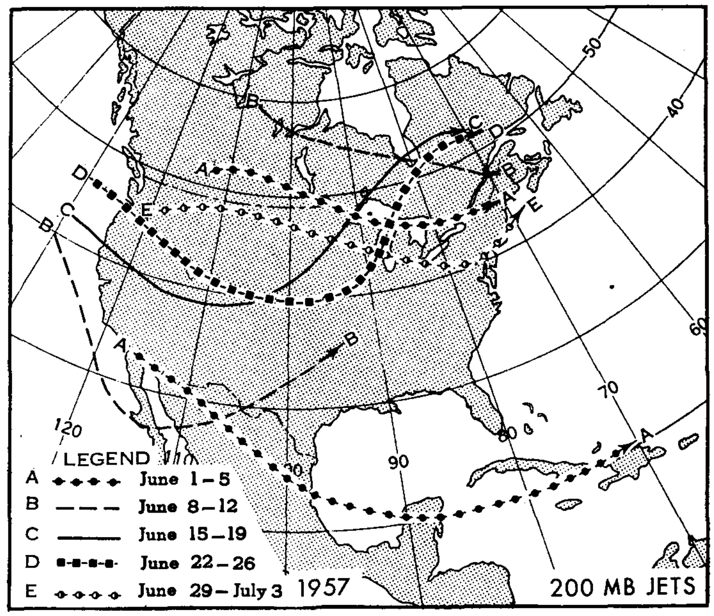

FIGURE 5.—Location of axis of mean jet stream during selected periods of June 1957, as obtained from a series of 5-day mean 200-mb. maps one week apart. The jet stream was split into two branches during the first two periods (A and B). During the remainder of the month (C, D, E) a single well-developed jet shifted progressively northward in the West and southward in the East.

of the Northeast. In the latter region a cold Canadian airmass carried by the stronger than normal northwesterly flow shown in figure 6A, dropped temperatures to record low levels at the end of the week. Hartford, Conn., recorded 38° F. on the 10th, the lowest June temperature ever observed there.

Over most remaining areas of the Nation both 700-mb. heights and surface temperatures averaged above normal. The strong ridge in the West was accompanied by temperatures over 6° F. above normal in most of the Plateau and Rocky Mountain regions. Daytime temperatures in the 90's caused rapid snowmelt in the mountains, resulting in floods along several rivers in Colorado.

The only significant precipitation in the United States during the first week of June occurred in southeastern and south-central portions of the country in connection with the upper Low over Texas and the moist southerly flow to its east. Locally heavy showers, ranging up to 6 inches on June 1 at Madill, Okla., aggravated the serious flood problem of May [3] in the Southern Plains and lower Mississippi Valley. Additional flooding was reported on the Red and Arkansas Rivers and their tributaries in portions of Texas, Oklahoma, Arkansas, and Louisiana. Another area of heavy rainfall, totaling from 2 to 6 inches, occurred in the Middle and South Atlantic States as a result of the passage of two cyclones. The first of these storms developed as a wave on the polar front in southern Virginia on June 5. The second was tropical in origin, forming in the eastern Gulf of Mexico on June 8. The

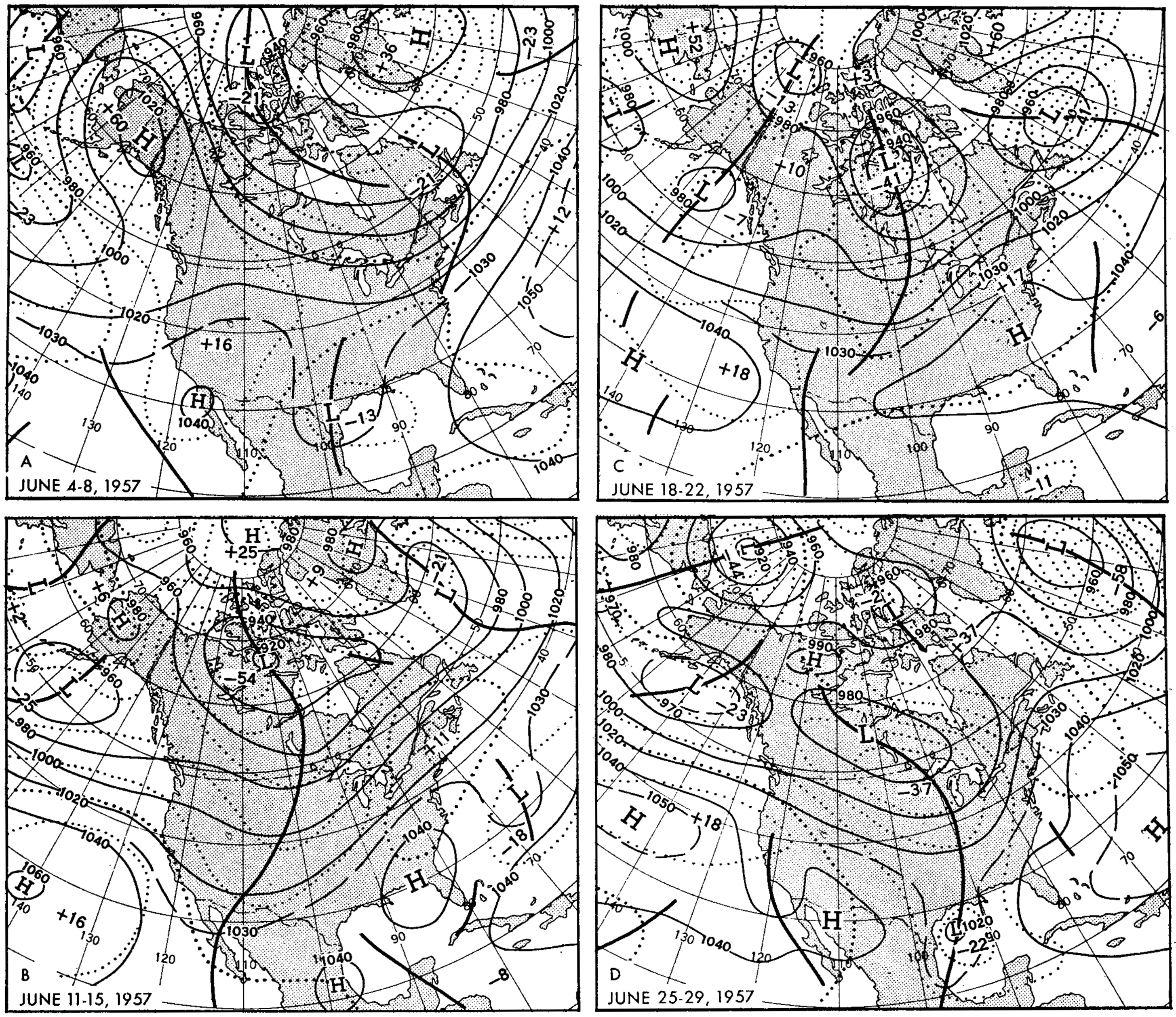

FIGURE 6.—Five-day mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for selected periods in June 1957 one week apart. Abrupt reversal in circulation from first to second week was followed by slow eastward motion of mean trough across central United States during remainder of month.

track of each of these storms, given in Chart X, closely paralleled the mean 700-mb. steering current indicated by the contours of figure 6A.

SECOND WEEK

The 700-mb. chart centered at the middle of the second week of June (fig. 6B) was quite different from the map for the first week (fig. 6A). Most of North America was now under the influence of a deep full-latitude trough extending from the Arctic Ocean through central Canada and the Great Plains of the United States into the Pacific Ocean off the coast of Mexico. A single, intense jet stream flowed around this trough at the 200-mb. level (fig. 5C). In the western half of the United States below normal 700-mb. heights (fig. 6B) and surface temperatures (fig. 7b) replaced above normal values of the first week, as cool Pacific airmasses were carried into the trough by stronger than normal northwesterly flow. Temperatures for the week averaged as much as 10° F. below normal at Grand Junction, Colo., while freezing weather was observed in parts of the Great Basin and central Rockies.

Precipitation was widespread in the cyclonic circulation over the normally arid southwestern quarter of the Nation, with amounts up to 2 inches in southeastern Utah (fig. 8b). Most of this rain (and some snow) was associated with the slow eastward motion of a complex surface and upper-level Low which developed in Nevada on the 9th

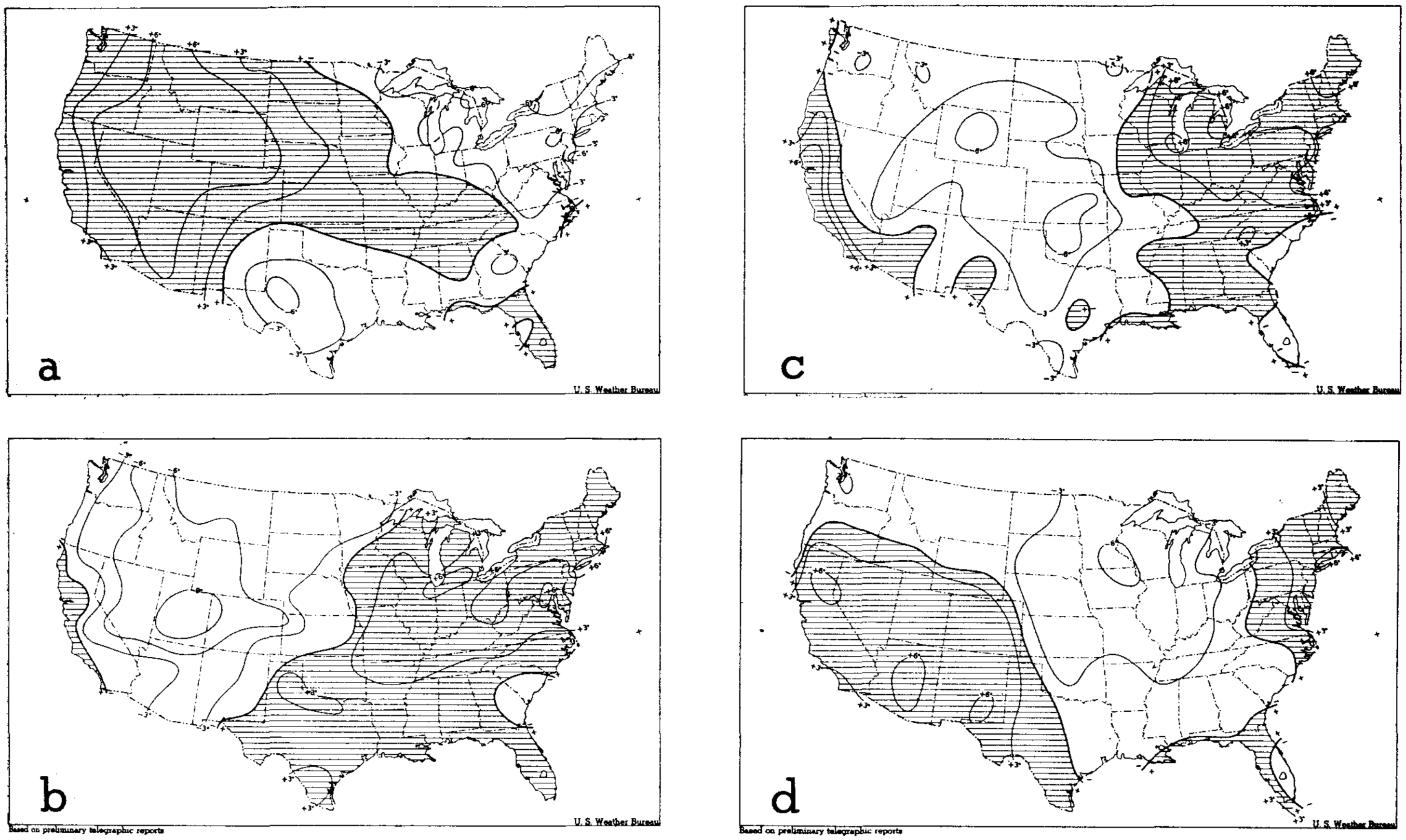

FIGURE 7.—Departure of average surface temperature from normal (° F.) for weeks in June 1957 centered on the 5-day mean periods shown in figure 6. Progressive eastward motion of pattern was apparent during last 3 weeks. (From *Weekly Weather and Crop Bulletin, National Summary,* for weeks ending (a) June 10, (b) June 17, (c) June 24, and (d) July 1.)

and dissipated in the Central Plains on the 12th (Chart X). It is noteworthy that most of the month's above normal precipitation in the Southwest (Chart III) fell during this second week.

Precipitation (fig. 8b) was also generally heavy in the moist southerly current east of the 700-mb. trough [5]. On the 14th and 15th a strong cold front separating cool Pacific from warm Gulf air became quasi-stationary in the upper Mississippi Valley. Excessive rains (up to 18 inches), accompanied by flash floods, fell in St. Louis and surrounding areas of Missouri and Illinois, and a tornado occurred in Springfield, Ill. As this front was carried northward by strong southerly winds in advance of an upper-level Low over the Rockies, heavy rains on the 16th and 17th caused serious flooding in parts of Kansas, South Dakota, and Minnesota. In the latter State, new 24-hour rainfall records of from 7 to 9 inches were established at a number of communities.

On the other hand, rains in Texas were neither as frequent nor as extreme as they had been in previous weeks, and the State received much-needed hot sunny weather in the latter part of the week. This desiccation was produced by the foehn effect in stronger than normal westerly components at 700 mb. (fig. 6B), and was related to the northward shift of the 200-mb. jet stream shown in figure 5.

The circulation in the eastern third of the United States was dominated by a strong ridge at 700 mb. (fig. 6B), with high center over northwestern Florida and center of above normal heights over New England. Above normal temperatures prevailed in and west of this ridge, with maximum departures for the week of more than 6° F. in the Northeast (fig. 7b). On the 16th, the mercury reached 100° F. in Philadelphia, setting a new record for the date, while at Burlington, Vt., 96° F. equaled the highest ever observed there in June. The persistence of anticyclonic circulation over the East inhibited the formation of precipitation, and less than half an inch of rain fell during the week along the entire Atlantic coast except for southern Florida and northern Maine (fig. 8b). The heat and continued lack of rain intensified the drought in southern New England.

THIRD WEEK

Little change occurred from the second to the third week in either the general circulation over North America (fig. 6C) or the patterns of temperature (fig. 7c) and precipitation (fig. 8c) over the United States. The trough in the United States sheared, with the main part moving slowly eastward across the Great Plains. The mean ridge along the east coast intensified somewhat as the center of the subtropical

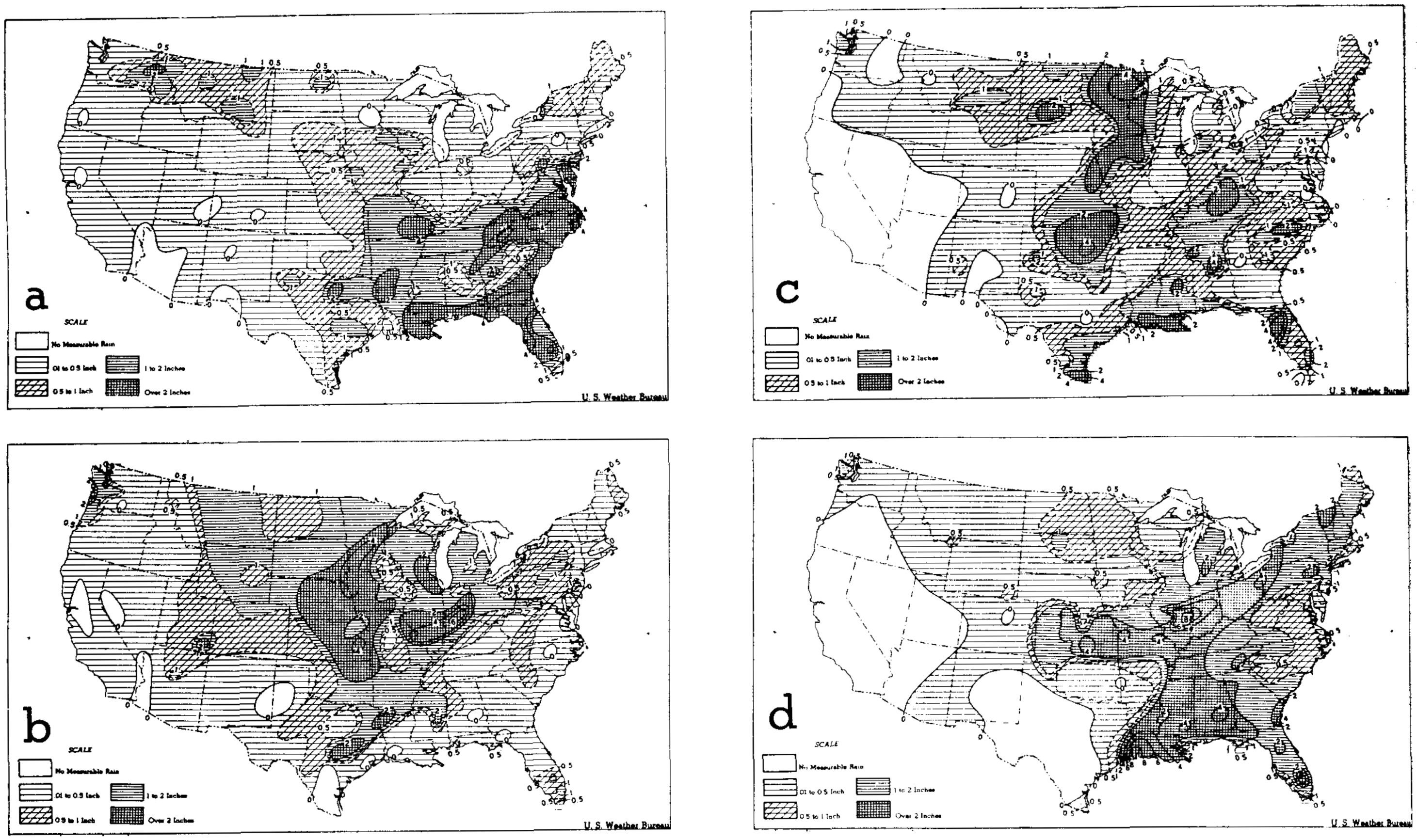

FIGURE 8.—Total precipitation (inches) for same weeks and from same source shown in figure 7. Heavy flood-producing rains (over 4 inches) fell in parts of the Great Plains and Mississippi Valley during each of the last 3 weeks of the month.

High moved northward from the Gulf coast into the South Atlantic States. The ridge along the west coast also strengthened, and a nose of the eastern Pacific High protruded into the southwestern United States where heights rose from below to above normal values.

The weakening of cyclonic circulation in the Southwest (fig. 6C) and the northward displacement of the jet stream (fig. 5) were accompanied by marked surface warming and drying. Temperatures for the week averaged more than 6° F. above normal in western California (fig. 7c), while practically no rain fell in the southwestern quarter of the Nation (fig. 8c). New record high temperatures for June were reported by San Diego, Calif., on the 18th (97.2° F.) and by Yuma, Ariz., on the 24th (120° F.). Several forest fires occurred in southern California, and fire hazard spread over the northern part of the State.

Hot dry weather also highlighted the week in the Northeast, where a persistent center of positive height anomaly (+170 ft., fig. 6C) remained quasi-stationary. For the second successive week, temperatures averaged about 6° F. above normal over a wide area from the Middle Atlantic States to New England and the Great Lakes. At Washington, D. C., the mercury reached 90° F. or above on eight consecutive days from June 12 to June 19. When the heat wave was broken by passage of a cold front from the west on the 19th and 20th, violent thunderstorms occurred in New England, with waterspouts and a tornado reported from New Hampshire. However, little or nor rain fell in coastal areas from Cape Cod to the Carolinas, and parts of New Jersey and southern New England were becoming critically dry.

Most of the remainder of the Nation experienced cool wet weather under the domination of the mean trough in the central United States. Rainfall was again heaviest just east of the trough, with more than 2 inches falling in a narrow band from Oklahoma north-northwestward to the Canadian border (fig. 8c). At Sioux Falls, S. Dak., a new 24-hour precipitation record was established when 4.33 inches fell on the 16th and 17th, causing serious floods on the Big Sioux River. Additional flooding occurred in portions of Minnesota, Kansas, Nebraska, Iowa, Wisconsin, and Oklahoma. One of the most notable storms of the week was a tornado in Fargo, N. Dak., on June 20. It is noteworthy that most of the severe local storms and heavy rains were observed in the vicinity of the 200-mb. jet stream, in the region where the axis curved cyclonically sharply northward (fig. 5, C and D). The week was unseasonably cool in the Great Plains, where temperatures averaged as much as 6° F. below normal. Damaging frost was reported in parts of Colorado, Oregon, and Nevada, while Topeka, Kans., had a record low of 52° F. on the 24th.

FOURTH WEEK

The principal features of the planetary wave train moved eastward over the United States during the final week of June (fig. 6D). The mean trough advanced from the Great Plains to the Mississippi Valley, its downstream ridge went from the east coast to the western Atlantic, a new trough started to develop along the west coast, and a strong high center appeared over the Southwest. The pattern of weekly temperature anomaly (fig. 7d) shifted eastward to a corresponding degree. Cyclonic circulation around the trough in the Mississippi Valley produced below normal temperatures from the Appalachians to the Great Plains. In the East the area of above normal temperatures contracted considerably as 700-mb. heights fell to below normal values, but strong southerly components in advance of the trough maintained warmer than average weather in the North and Middle Atlantic States. The area of abnormal warmth in the Southwest expanded eastward to the Gulf of Mexico and northward to Idaho. At Roswell, N. Mex., temperatures climbed to 105° F. or higher each day from the 25th to the 30th in the worst June heat wave since 1896, while 107° F. in El Paso, Tex., on the 28th was a new absolute record for that station.

The week's rainfall pattern (fig. 8d) also shifted eastward relative to the previous week. Practically all districts in the western third of the country reported total precipitation of less than half an inch, and a vast area from southern Texas northwestward to Oregon had no rain at all. This dry regime was the result of anticyclonic circulation at 700 mb. (fig. 6D) and northward shift of both the jet stream at 200 mb. (fig. 5) and the principal cyclone track at sea level (Chart X).

Except for continuing drought along the Atlantic coast from Cape Cod to Hatteras, nearly all sections of the country east of the Great Plains experienced abundant rainfall, generally in excess of one-half inch. Most of this rain fell in the cyclonic circulation around the mean trough in the Mississippi Valley or in the southerly flow to its east. The greatest amounts, over 2 inches, were observed in two separate zones which merged over the Ohio Valley. From here one band extended west-southwestward into Kansas, the other south-southwestward to the Gulf coast. The first belt of heavy rain was primarily frontal in nature, occurring along a slow-moving cold front from the 26th to the 28th. Rainfall totaled as much as 5 inches in Kansas, 7 inches in Missouri and Indiana, and 11 inches in Illinois. Severe flooding of farmland resulted in these States. The second belt of heavy rain paralleled the path of hurricane Audrey from the Texas-Louisiana border to western New York. Since this hurricane was undoubtedly the weather highlight of the week, and probably of the month, it is discussed separately in the next section.

4. FORMATION AND BEHAVIOR OF HURRICANE AUDREY

Hurricane Audrey, which formed in the southwestern Gulf of Mexico in the early hours of June 25, has been described as "probably the worst June hurricane on record" [17]. It was responsible for the loss of over 500 lives, the largest death toll attributed to any storm in the United States since the New England hurricane of September 21, 1938, and the largest due to any storm in the Gulf since the Galveston hurricane of September 8, 1900. Most of these deaths were caused by drowning in record high tides of from 9 to 11 feet along the coast of Louisiana on the morning of the 27th. As Audrey traversed the continental United States it was partly responsible for additional deaths and damage from several tornadoes in Mississippi, Louisiana, and Alabama; floods in Indiana and Illinois; and high winds in Pennsylvania and New York (up to 100 m. p. h. in Jamestown, N. Y.). Further details about the destruction caused by this hurricane can be found in a special issue of the *Weekly Weather and Crop Bulletin, National Summary* [17]. A detailed analysis of the synoptic situation during its life history is contained in the adjoining article by Ross and Blum [14]. The balance of this paper will deal with the climatological background and longer range aspects of this destructive storm.

Figure 9 contains a sequence of partially overlapping 5-day mean 700-mb. charts as routinely analyzed in the preparation of extended forecasts on Sunday, Tuesday, and Thursday of each week. The series starts with the period from June 15 to 19 (fig. 9A), when the subtropical high center in the eastern United States, which had started to develop during the second week of June (fig. 6B), attained maximum intensity (10,590 ft.) and farthest northward displacement (West Virginia). To its south a broad stream of easterlies occupied the entire Caribbean and Gulf of Mexico. Three days later (fig. 9B) this easterly current acquired more cyclonic curvature as the High weakened somewhat (10,500 ft.) and retreated southward to the Carolinas. By the next map of the series (fig. 9C), a distinct easterly wave had developed in the Gulf of Mexico, while the High remained unchanged over the Carolinas.

Meanwhile the deep polar trough (in the westerlies) which had developed in the Great Plains and southwestern United States during the second week of June (fig. 6B) was moving slowly eastward across the central United States (fig. 9 A, B, C). By the period June 22–26 (fig. 9D) it was located directly north of the easterly wave in the Gulf of Mexico, and a single trough extended southward near the 95th meridian from Minnesota to Central America. According to Cressman [2], such latitudinal superposition frequently produces intensification of both disturbances. In accordance with this hypothesis, a weak closed Low with central height of 10,300 feet formed within the easterly wave in the Gulf (fig. 9D). It was in

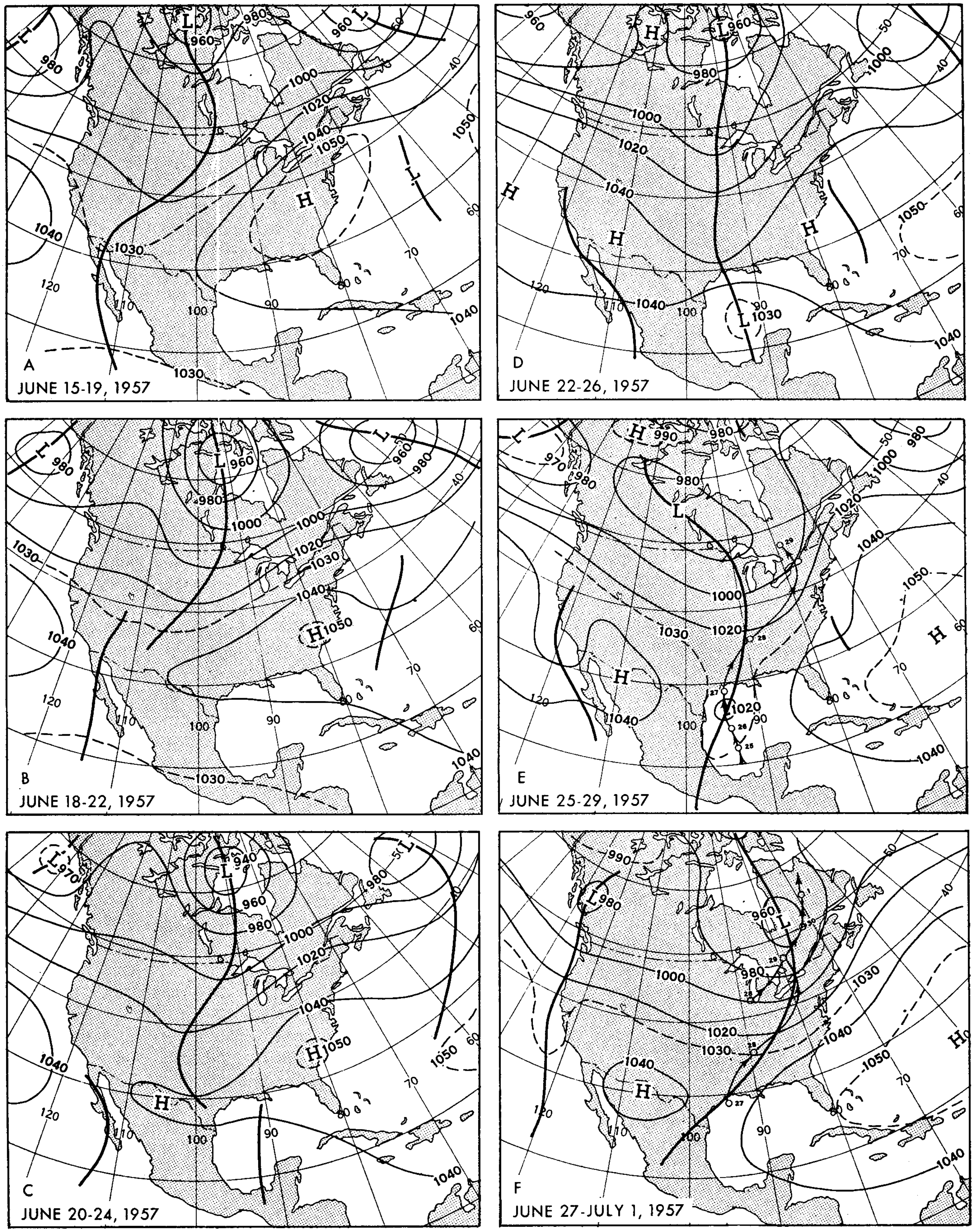

FIGURE 9.—Thrice-weekly, 5-day mean 700-mb. maps (in tens of feet) showing sequence of events prior to and during life history of hurricane Audrey. Track of the hurricane at sea level is shown by the arrows in E for the period June 25–29 and in F for the period June 27–July 1, with position at 1200 GMT indicated by open circles and date along trajectory. During both periods the storm moved sharply northward along the axis of the mean trough.

this Low that Audrey developed, reaching hurricane intensity on the 25th. Its subsequent trajectory across the Gulf of Mexico, United States, and Canada is given by the arrows in the last two maps of the sequence (fig. 9E, F). As Audrey moved northward it entered the westerlies, appearing as a 10,200-foot Low at the southern end of the polar trough on the map for June 25–29 (fig. 9E), and merging with the polar Low near James Bay from June 27 to July 1 (fig. 9F).

The evolution portrayed in figure 9 is illustrated in a somewhat different fashion in figure 10. This chart gives the tracks of the two centers of 5-day mean negative height departure from normal corresponding to the easterly wave and polar trough depicted in figure 9. Figure 10 shows that a negative anomaly first appeared as a weak center (−80 ft.) in the western Caribbean during the 5-day period June 11–15. It subsequently meandered slowly westward across Central America with little change in intensity until it entered the western Gulf of Mexico as a more pronounced center (−140 ft.) during the period June 22–26, when it corresponded to the closed Low shown in figure 9D. Meanwhile the center of below normal heights in the polar trough had been moving slowly eastward across the northern border States. This center apparently merged with or absorbed the tropical center when Audrey accelerated sharply northward (around June 29), so that only a single intense center of negative anomaly (as much as −420 ft.) in eastern Ontario was evident on the maps for June 27 to July 1 and June 29 to July 3.

One of the most significant aspects of figure 10 is the fact that a center of negative height anomaly ultimately associated with hurricane Audrey could be located and traced as a distinct entity on every 5-day mean map starting as early as the period centered June 13. No other single feature of daily or mean maps could be followed by the author with equal facility for so long a period prior to hurricane formation. The quasi-conservative nature of this height anomaly may warrant further research along these lines for other hurricanes.

Another factor investigated in connection with the development of hurricane Audrey was sea surface temperature, since Palmén [11] concluded that hurricanes can be formed only in oceanic regions outside the vicinity of the Equator where the surface water has a temperature above 78°–81° F. All ship observations of water temperature plotted on twice-daily synoptic charts during June were therefore tabulated for the 5° squares delineated in figure 11. The mean temperatures were computed by 10-day periods (and for the entire month) and plotted in the center of each square. These means were then compared with the long period (1887–1936) averages given by Riehl [13]. The departures from this "normal" are given in figure 11, along with the number of observations in each box. It is apparent that, throughout the month, the sea surface was warmer than both the critical temperature of 81° F. and the long-period average in practically all por-

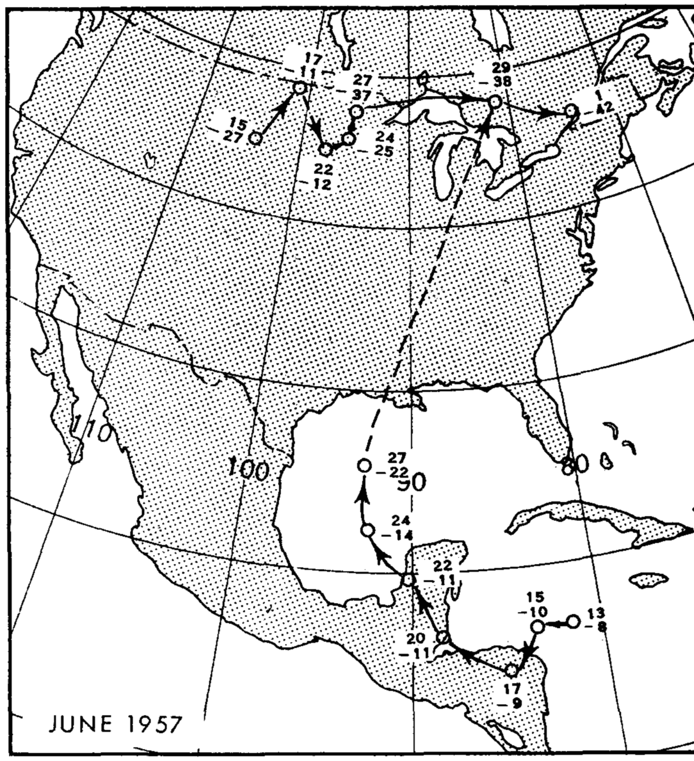

FIGURE 10.—Tracks of two centers of negative height anomaly from a series of overlapping 5-day mean 700-mb. height departure from normal maps (prepared three times a week) from June 13 to July 1, 1957. Beside each open circle, indicating the location of the anomaly center at map time, is plotted the date of the middle day of the period (above) and the central intensity in tens of feet (below). Trajectory is dashed in region of uncertain continuity. Note that the negative anomaly subsequently associated with hurricane Audrey can be traced back as far as the period June 11–15, 1957.

tions of the Caribbean and Gulf of Mexico. It is particularly noteworthy that in the square where Audrey developed, indicated by a hurricane symbol in figure 11C, temperatures rose steadily during the month to a maximum of 85° F., 3° above normal, during the period June 21–30. Although this value is based upon only three observations, it is substantiated by the temperature of 84° F. in adjacent squares to the north and east, where a large number of observations were available.

It has been indicated that both the 700-mb. circulation and the surface water temperatures were favorable for the development of hurricane Audrey. The 200-mb. circulation was considered next since it is well known that strong outflow is required at high levels above a tropical depression before it can intensify to hurricane strength. According to Riehl [12], such divergence is most likely to occur when the storm lies under northerly flow east of an upper (200-mb.) High, where the curvature of the high-level flow is anticyclonic or changes from cyclonic to anticyclonic. In a more recent paper [15] he adds that "For extreme deepening the anticyclone above the hurricane should also be part of a ridge of the long wave pattern in

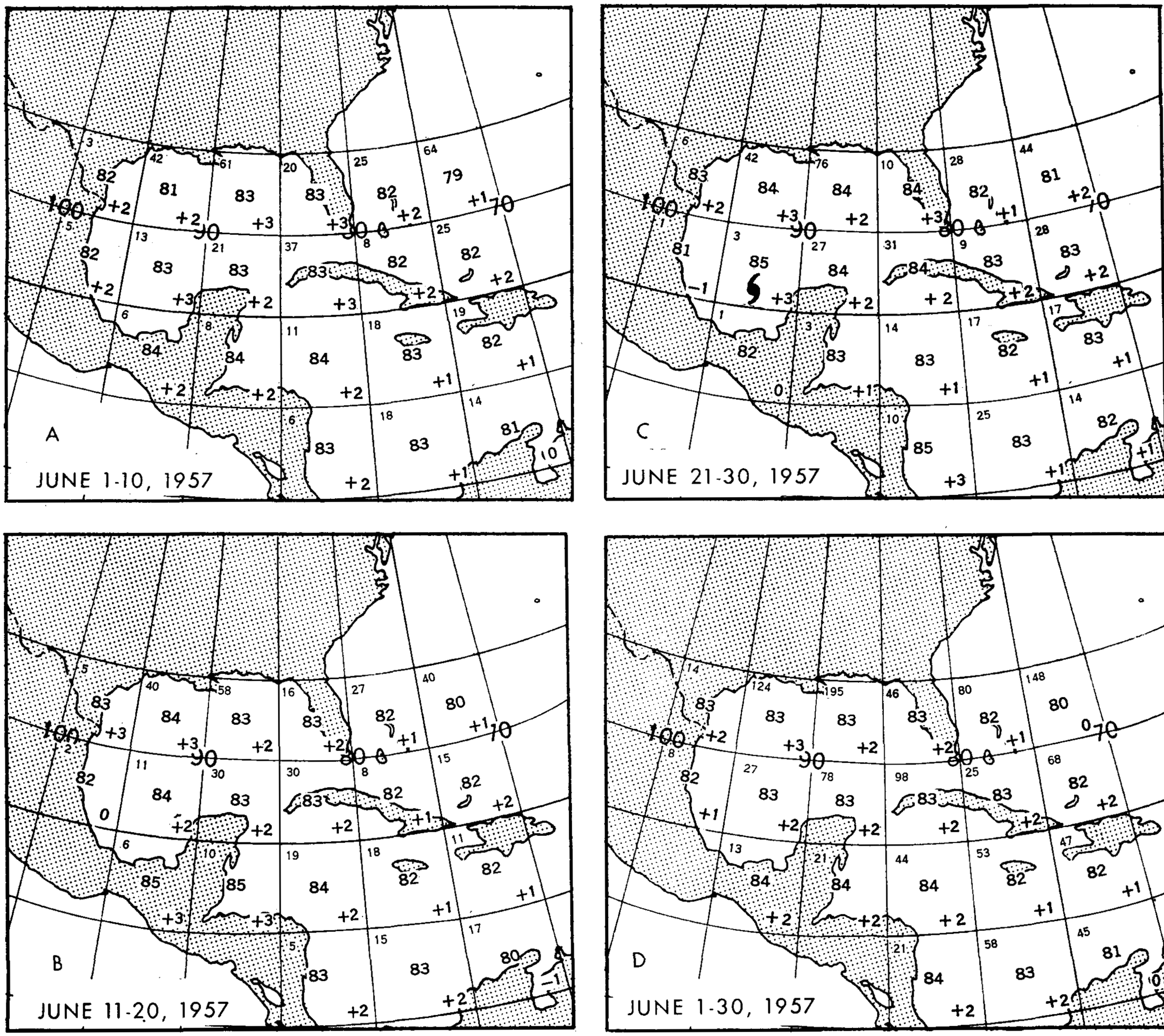

FIGURE 11.—Mean sea surface temperatures (° F.) by 5° squares for each decade in June 1957 (A, B, C) and for the month as a whole (D). Numbers in lower right hand corner of each box give the departure from normal in ° F., figures in upper left give the number of ship observations (from daily synoptic maps) on which the data are based. Water temperatures were especially warm in the area where Audrey formed (indicated by the hurricane symbol in C).

the westerlies during a period with considerable amplitude."

That these conditions generally existed in this case is indicated by figure 12, which gives the 5-day mean contours at the 200-mb. level for June 22–26, the period just prior to and during which Audrey (located by the hurricane symbol) actually developed (on June 25). A similar development early in the month, when the sea surface was already warm (fig. 11 A, B) was precluded by the presence of the southern branch of the jet stream shown in figure 5 (A and B), since the Gulf of Mexico was then in the zone of baroclinic westerlies. It was only later in the month, when the jet was farther north and an upper level anticyclone began to develop in the Tropics, that hurricane formation was favored. Thus the transition within the month of June (described in section 3) from a spring type to a summer type of circulation was an important part of the climatological background for hurricane Audrey.

Audrey's track, subsequent to its formation, can also be related to the mean circulation. Namias [9] showed that the paths of both Atlantic hurricanes and Pacific typhoons were roughly parallel to the isopleths of 700-mb. height departure from normal on monthly mean maps for Septem-

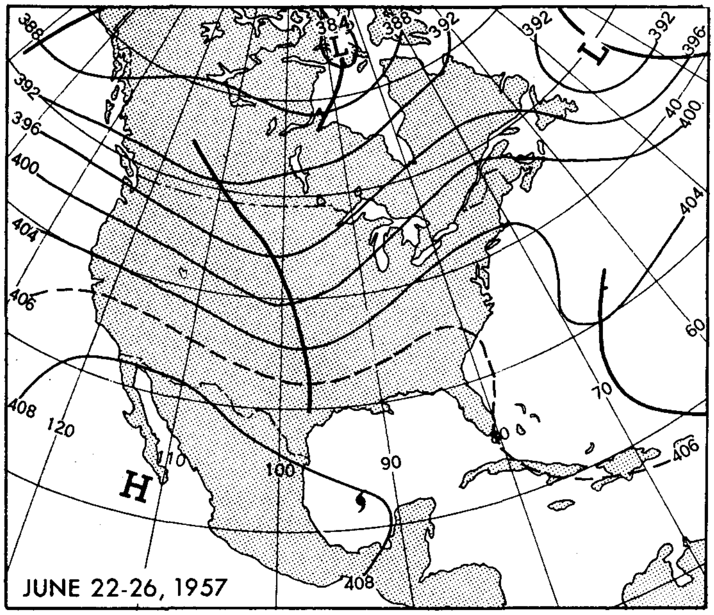

FIGURE 12.—Five-day mean 200-mb. contours (in hundreds of feet) for June 22–26, 1957, the period just prior to and during the development of Audrey. In the area where Audrey formed (indicated by the hurricane symbol) the flow was northerly, and the curvature changed from cyclonic to anticyclonic.

ber 1944 and 1938. A similar relation existed in this case, as can be seen by comparing the trajectory of hurricane Audrey from June 25 to 29 shown in figure 9E with either the 5-day mean 700-mb. anomalies for the same period, given as dotted lines in figure 6D, or the monthly mean anomalies in figure 4.

Also striking was the manner in which this hurricane moved sharply northward along or just east of the axis of the mean trough (fig. 9E). Even after the storm became extratropical in character (about June 28) it crossed the mean contours toward lower height, as illustrated in figure 9F for the period from June 27 to July 1. This tendency for Audrey to move up the trough line may reflect a force driving cyclonic vortices toward regions of higher absolute vorticity, as postulated by Kuo [8] and previously illustrated for extratropical cyclones [6]. Even if this relation is merely a statistical reflection of the effect of the storm upon 700-mb. heights in the region it traverses, it can still be useful as a consistency check and as a prognostic aid in interpreting the mean flow pattern in terms of its daily components. At any rate, this type of behavior can be noted by comparing hurricane tracks with mean trough positions given in many previous articles of this series; for example, it is illustrated for 5-day mean maps in the articles on weather and circulation for the months of September 1951, August 1954, June 1956, and September 1956, and for 30-day means in the articles for August 1950, September and October 1953, September 1954, August 1955, and August 1956.

One of the more intriguing aspects of Audrey's behavior was the way it accelerated and deepened rapidly from a central pressure of 995 mb. in Tennessee on the morning of June 28 to a pressure of 974 mb. just northeast of Lake Huron on the 29th (fig. 9F). This deepening occurred through combination of the hurricane with a wave which formed on the polar front near Chicago on the 28th. A more complete discussion of this process can be found in the following article [14]. It was accompanied by rapid eastward motion of the mean trough from the Mississippi Valley to the Appalachians (fig. 9F), so that during the last 5 days of June the east coast region was occupied by cyclonic instead of anticyclonic flow for the first time in 3 weeks. At the same time a new mean trough extended along the west coast from 20° N. to 60° N., and a mean ridge occupied the Rockies. By the next 5-day period (June 29 to July 3) the 200-mb. jet stream (fig. 5E) was curved sharply anticyclonically in the West and cyclonically in the East. This was indicative of a new circulation regime, more typical of summer, which was to dominate the month of July. These events were reminiscent of the passage of hurricane Hazel in October 1954 [7] since this storm also underwent baroclinic deepening in the northeastern United States coincident with a complete change of circulation pattern over the entire country.

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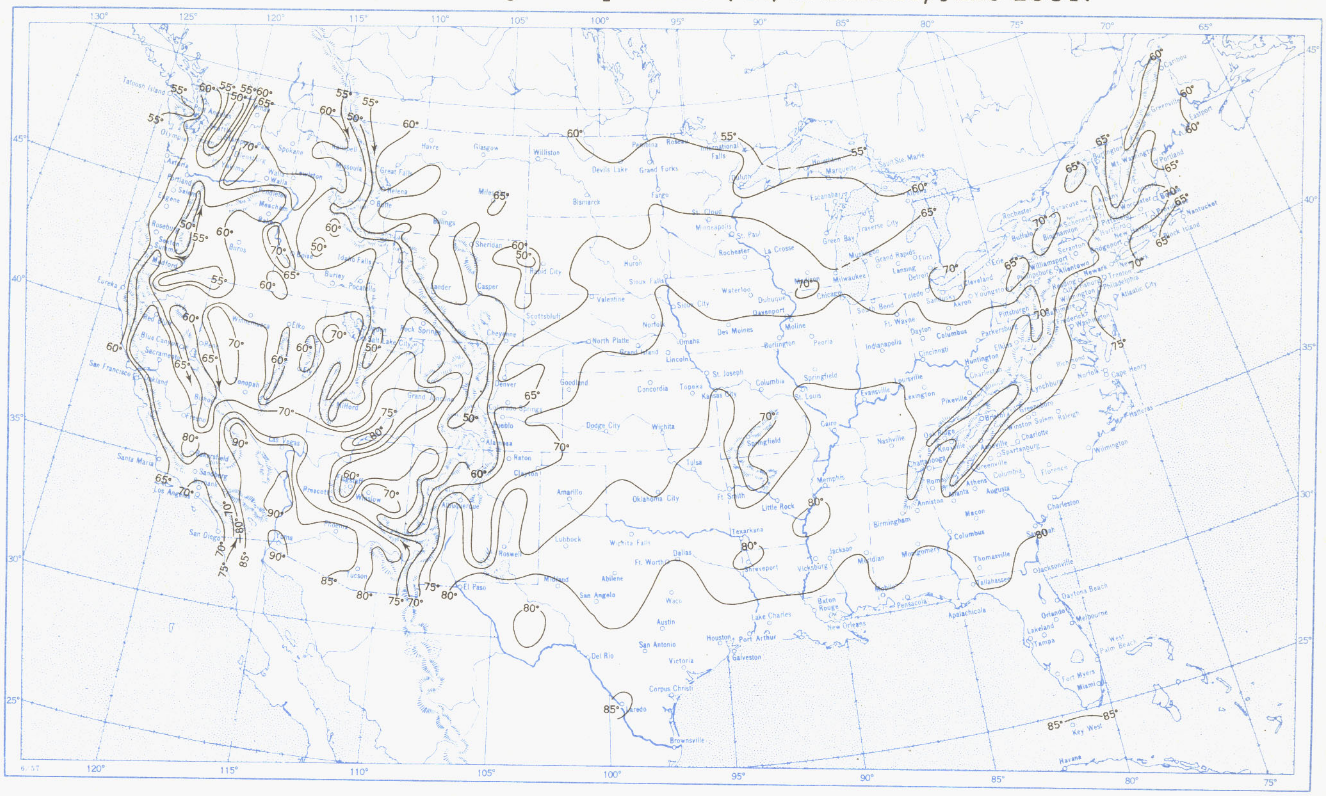
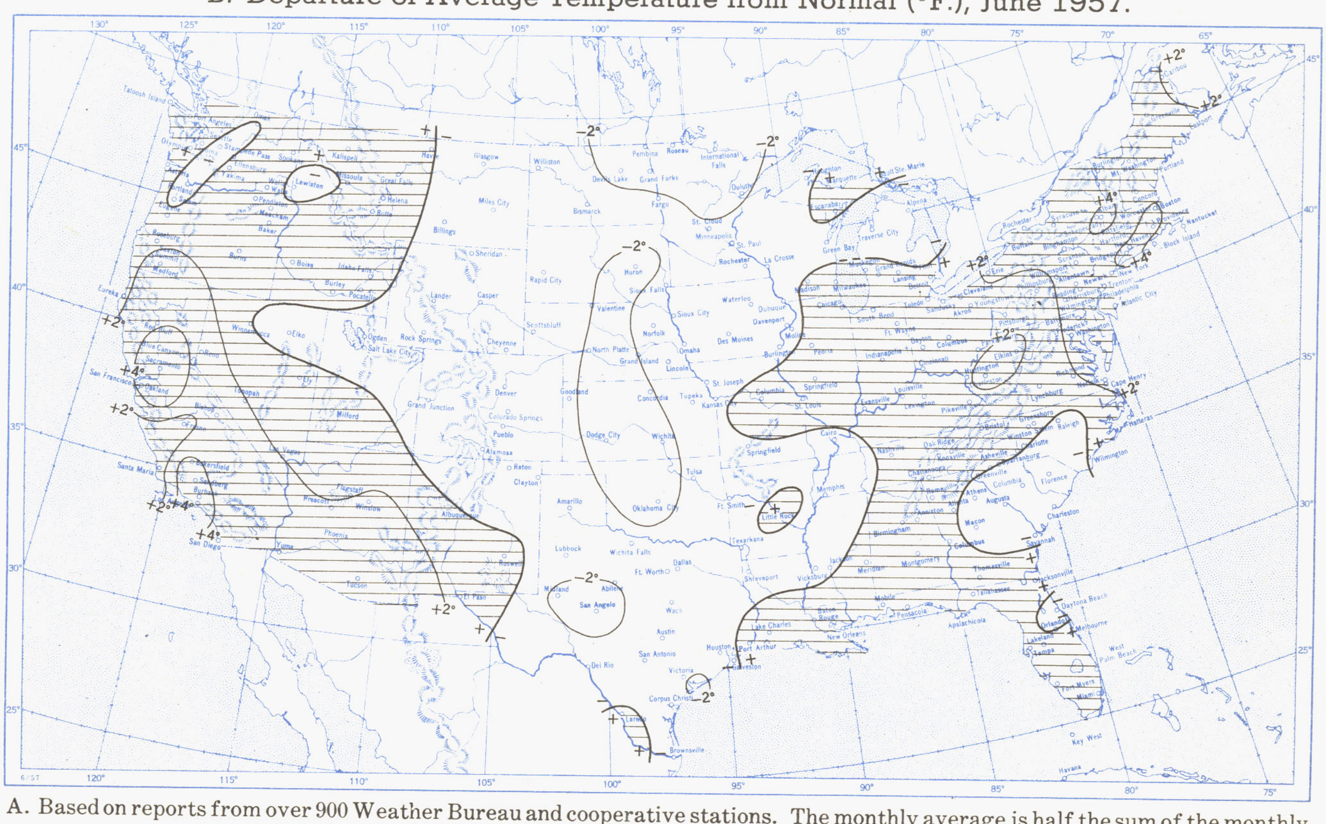
CORRECTION

MONTHLY WEATHER REVIEW, vol. 85, No. 4, April 1957, p. 120: Legend to figure 1 should read "Relation between dry bulb temperature at 4:45 p. m. PST," instead of "dewpoint temperature."

Chart I. A. Average Temperature (°F.) at Surface, June 1957.

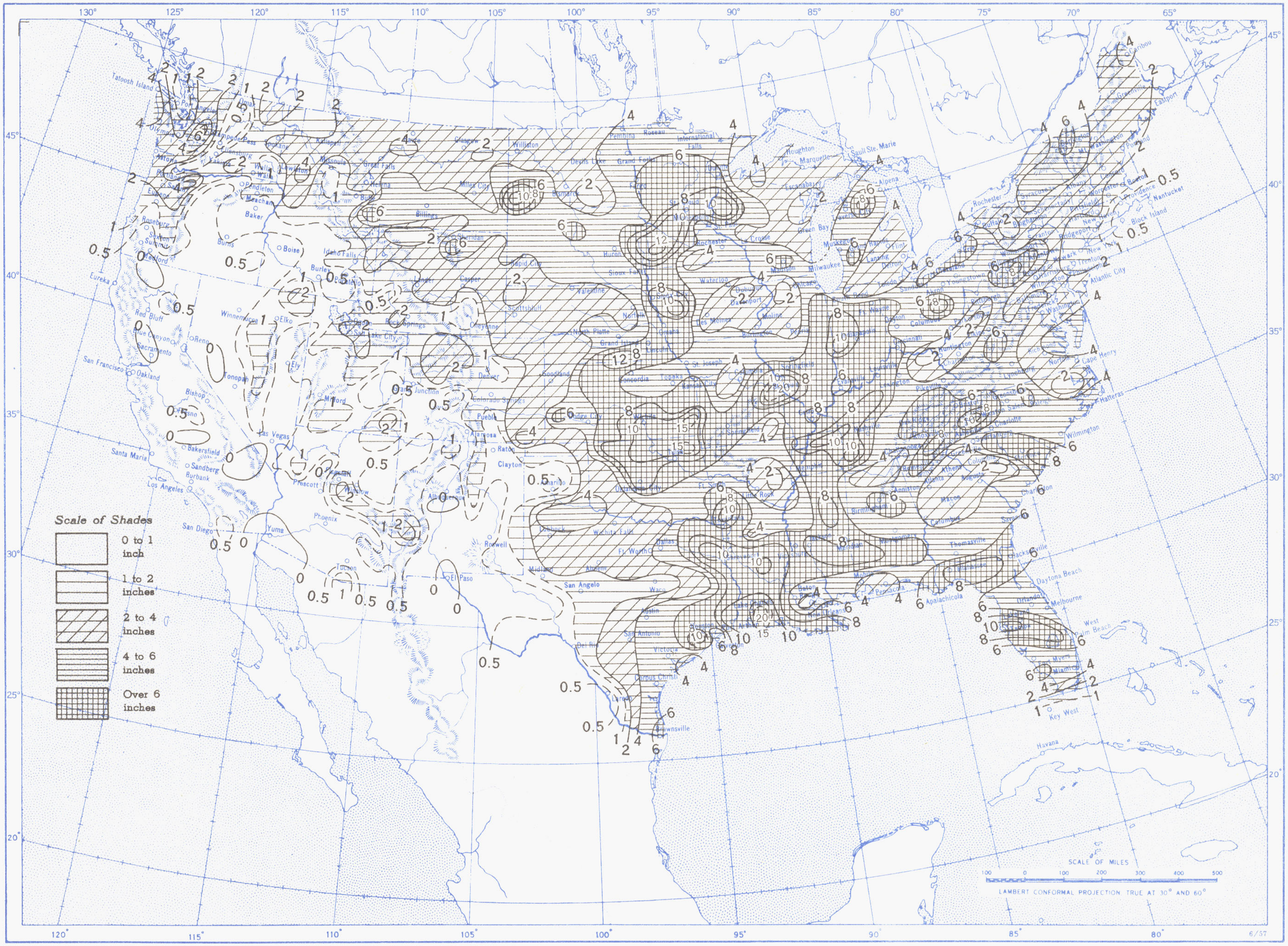


B. Departure of Average Temperature from Normal (°F.), June 1957.



A. Based on reports from over 900 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Departures from normal are based on the 30-yr. normals (1921-50) for Weather Bureau stations and on means of 25 years or more (mostly 1931-55) for cooperative stations.

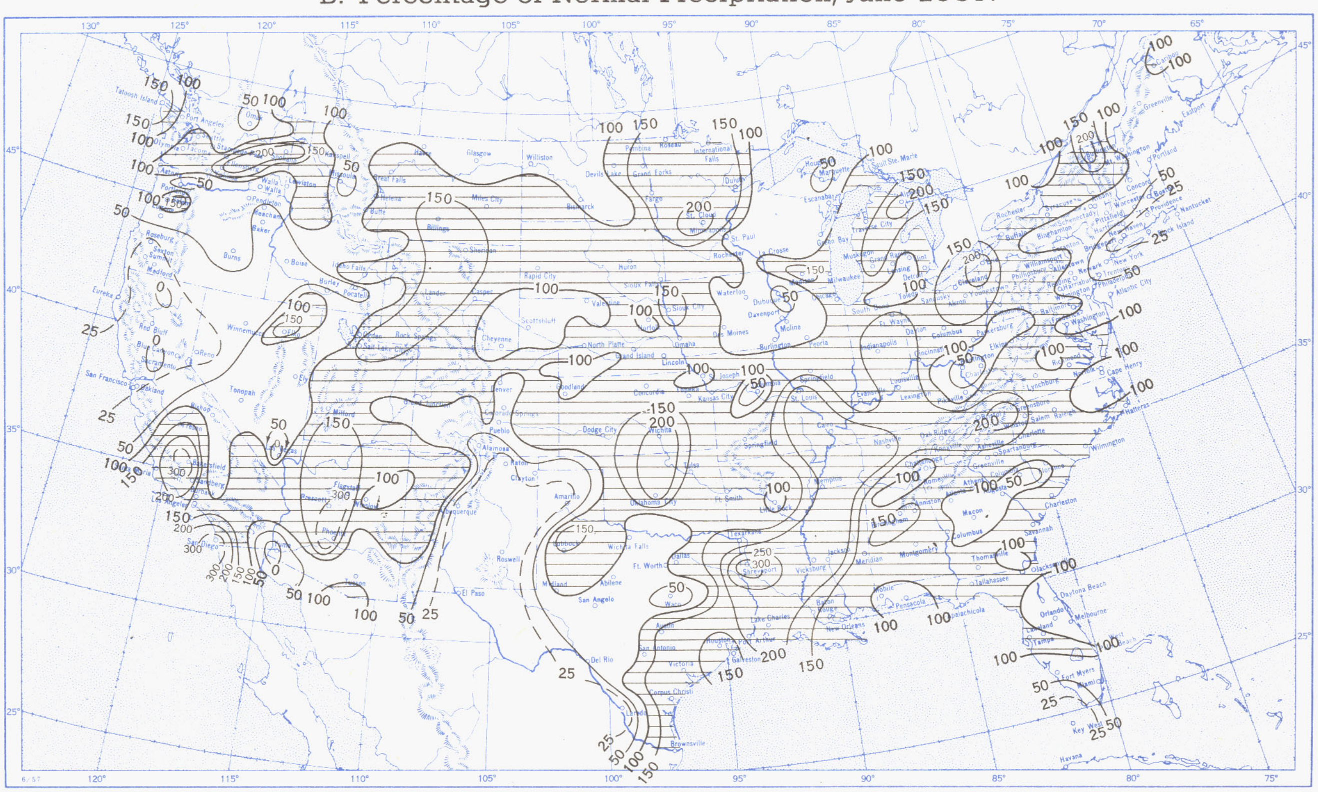
Chart II. Total Precipitation (Inches), June 1957.



Based on daily precipitation records at about 800 Weather Bureau and cooperative stations.

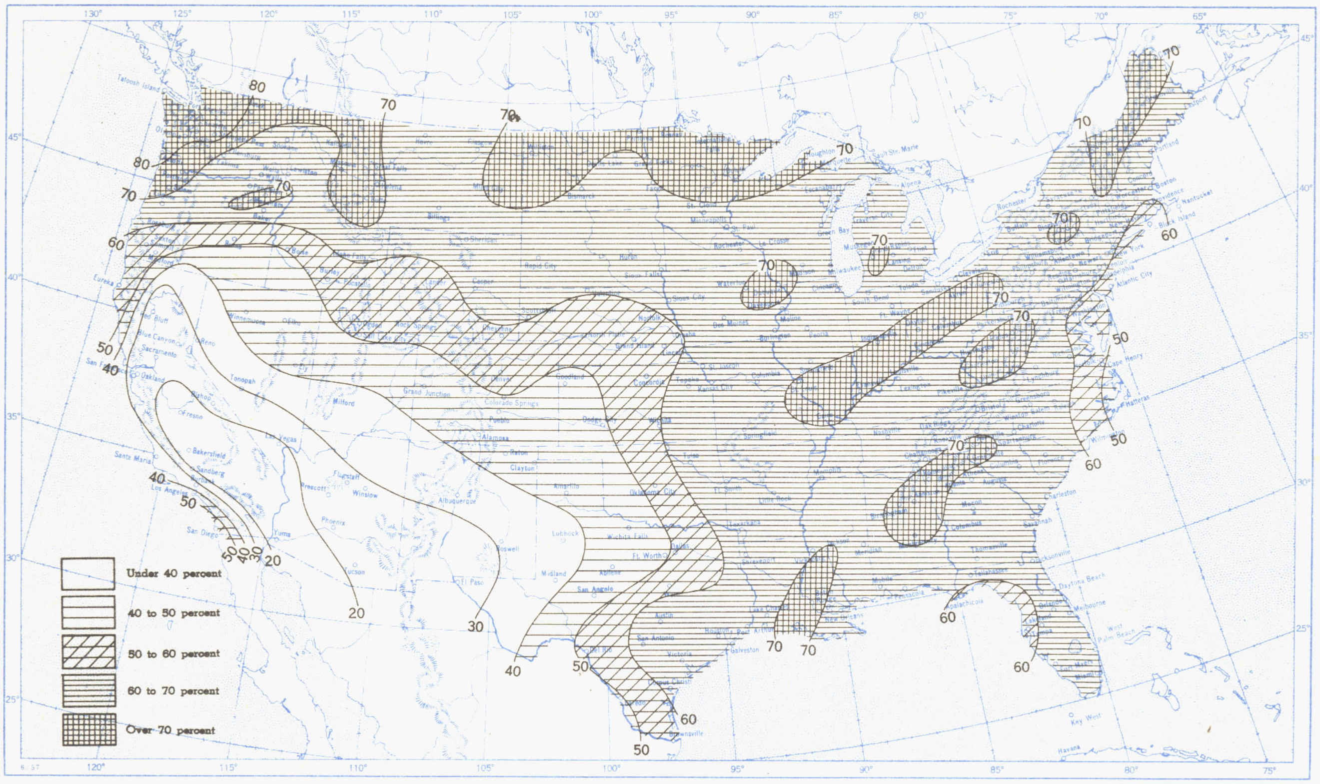
Chart III. A. Departure of Precipitation from Normal (Inches), June 1957.

B. Percentage of Normal Precipitation, June 1957.

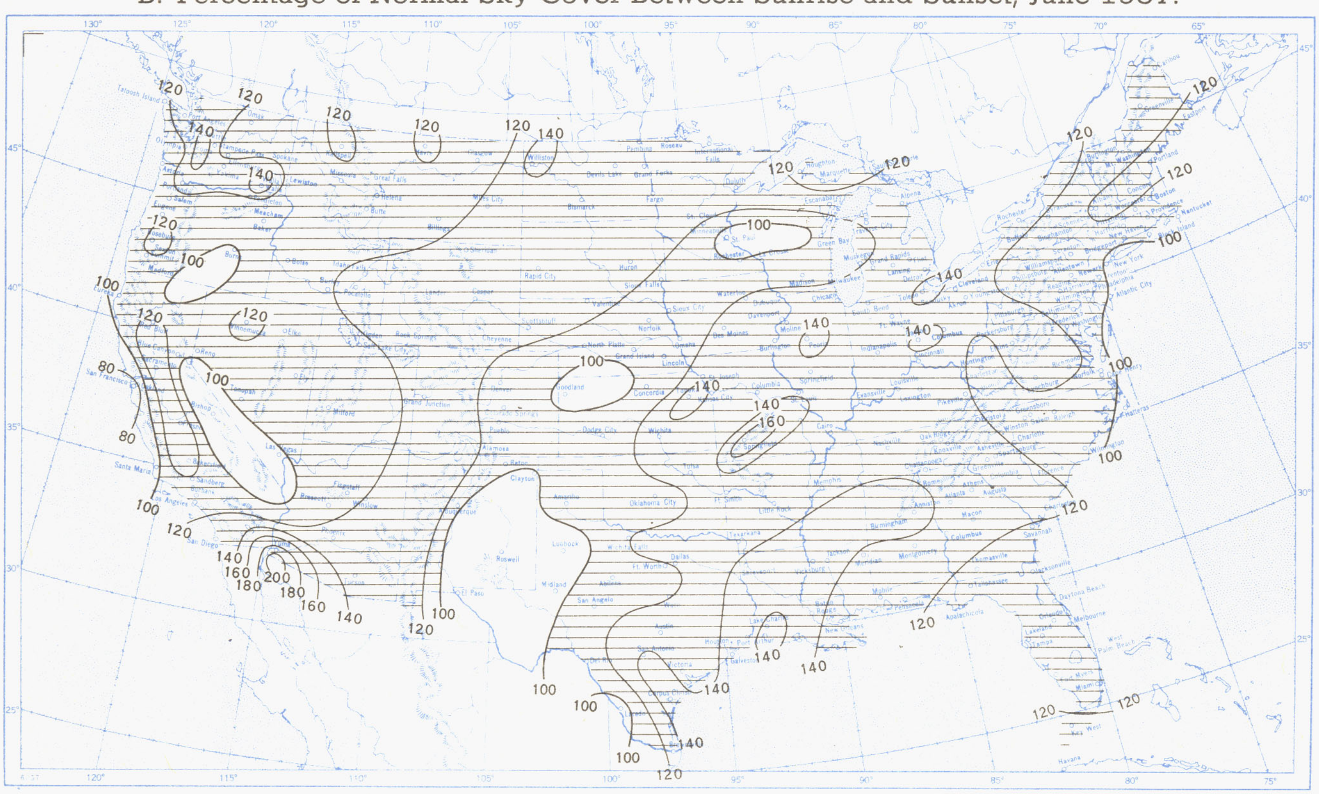


Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, June 1957.

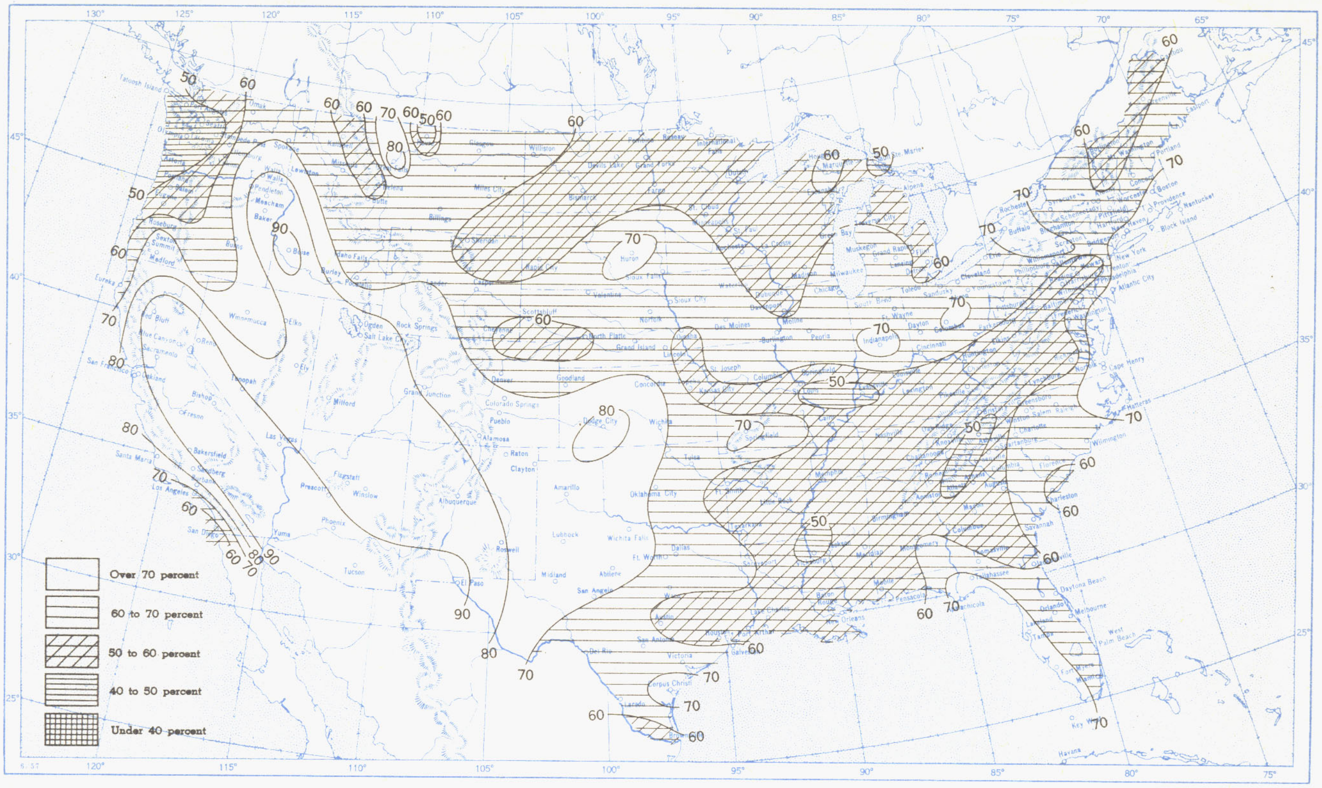


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, June 1957.

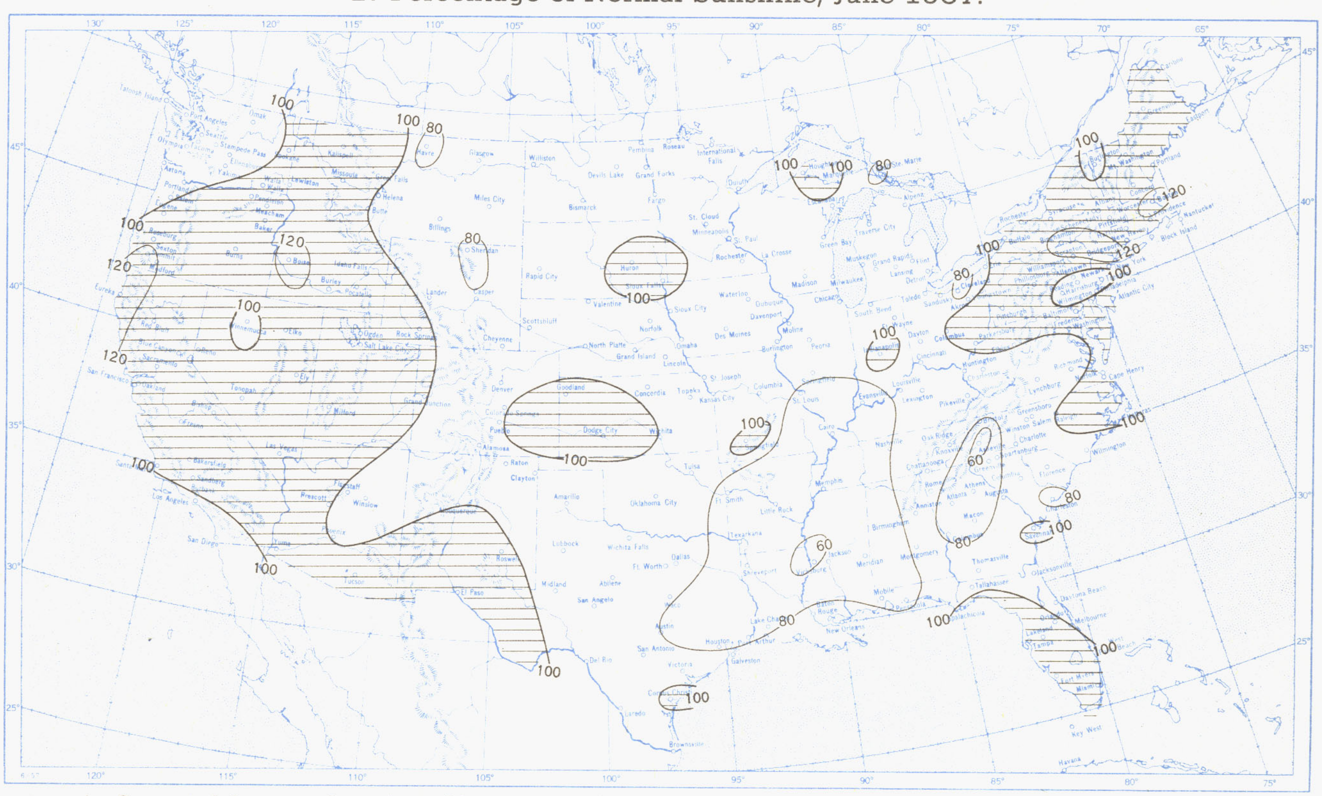


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, June 1957.



B. Percentage of Normal Sunshine, June 1957.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, June 1957. Inset: Percentage of Mean Daily Solar Radiation, June 1957. (Mean based on period 1951-55.)

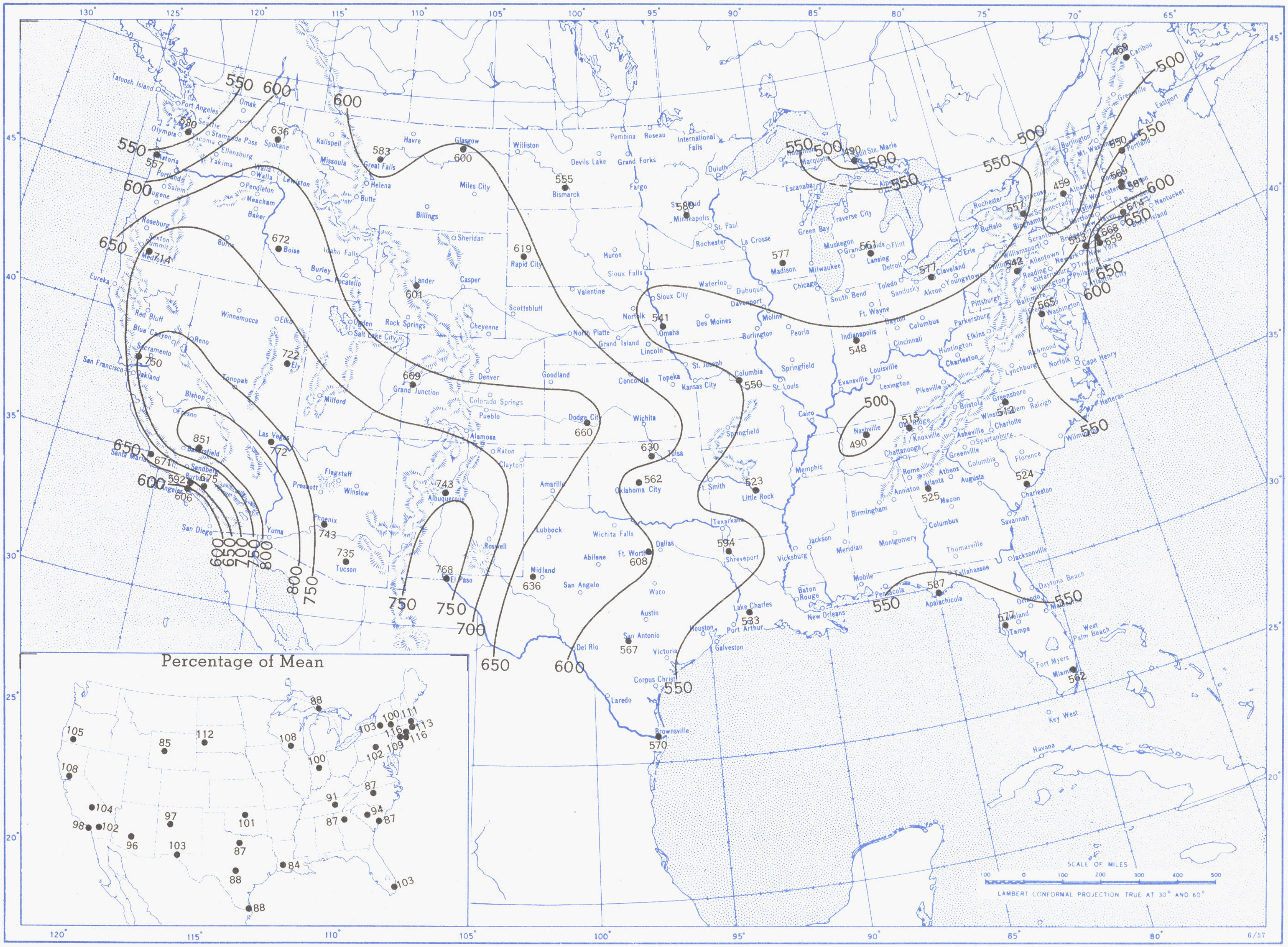
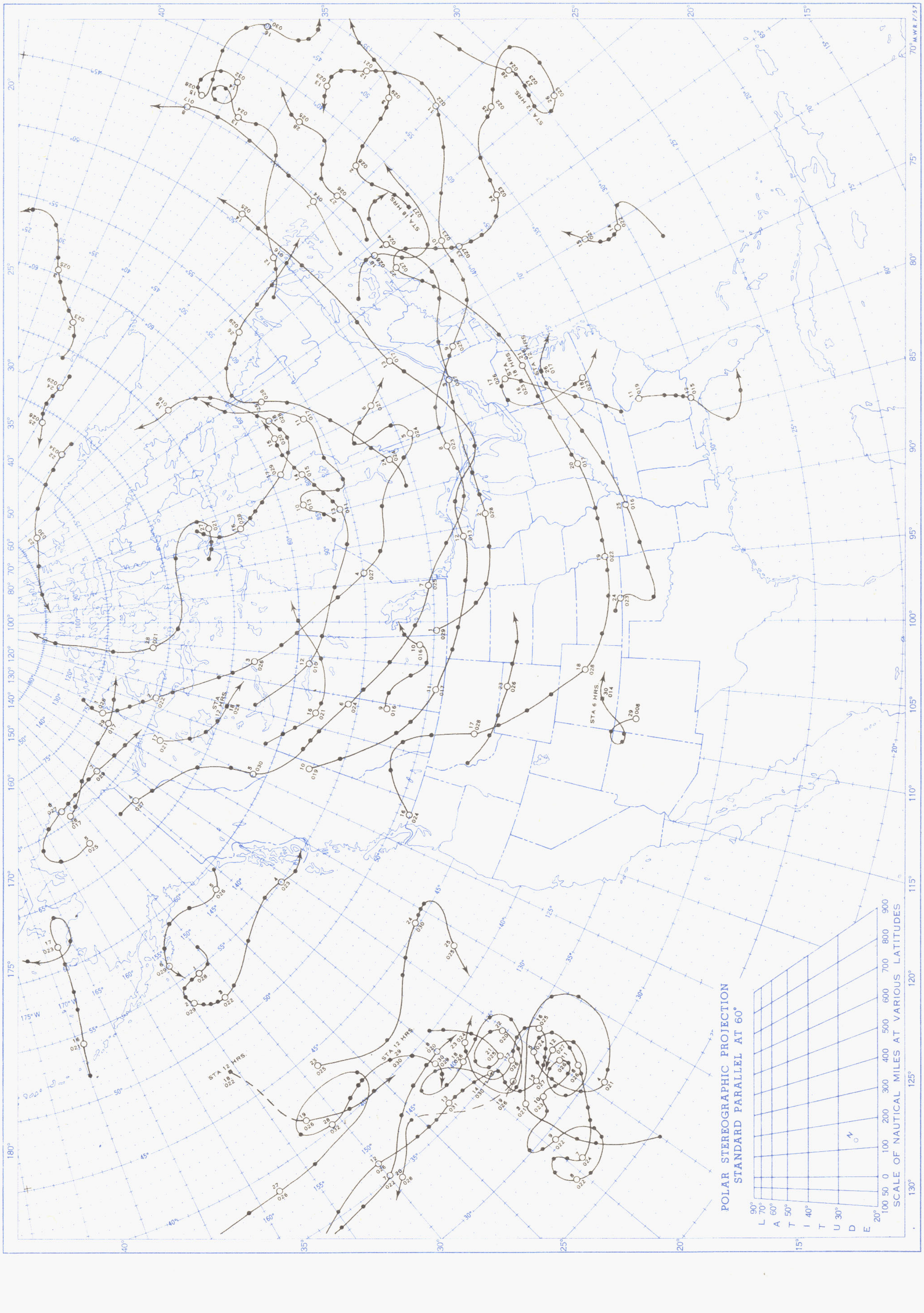


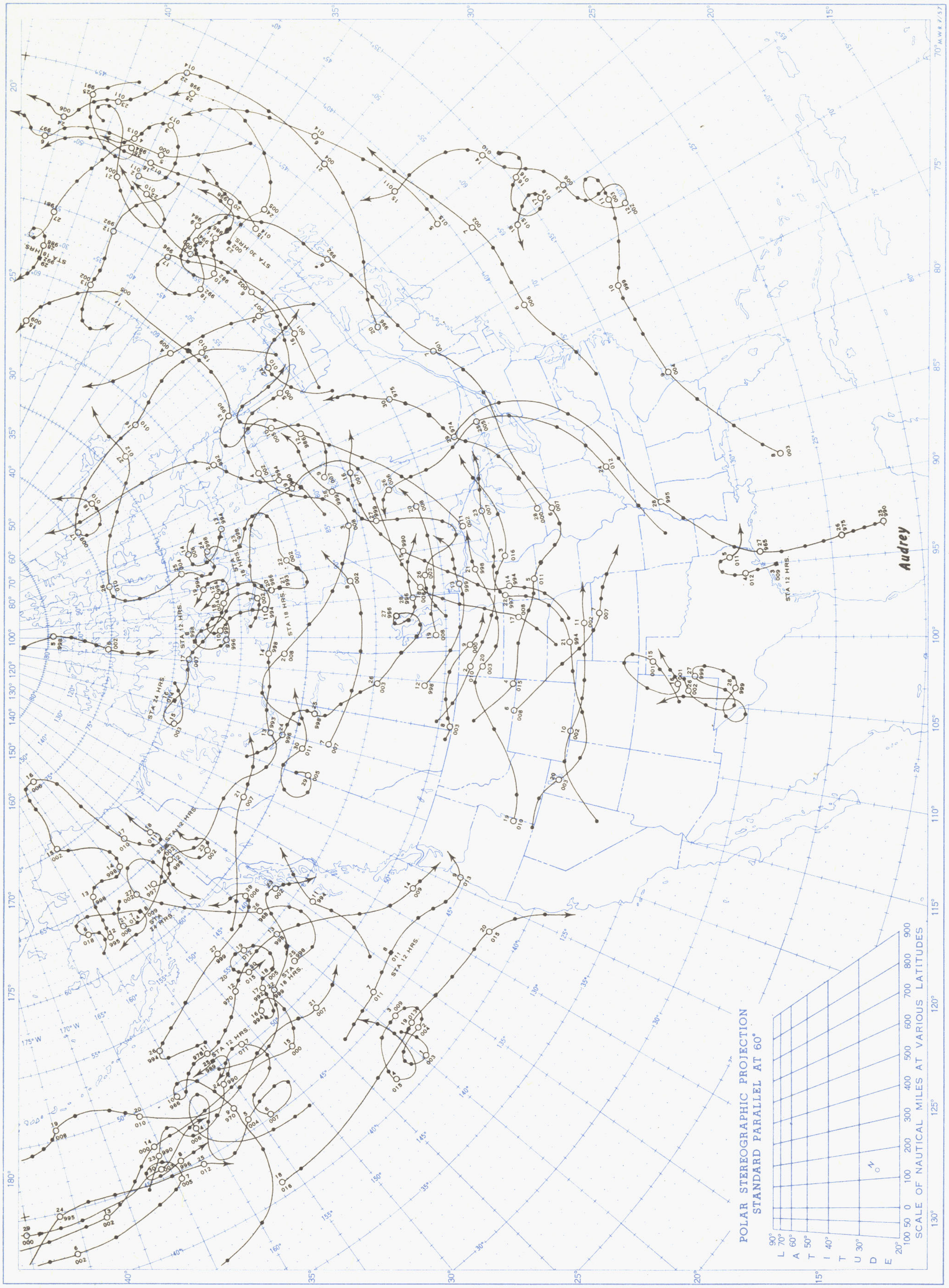
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.$^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. The inset shows the percentage of the mean based on the period 1951-55.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, June 1957.



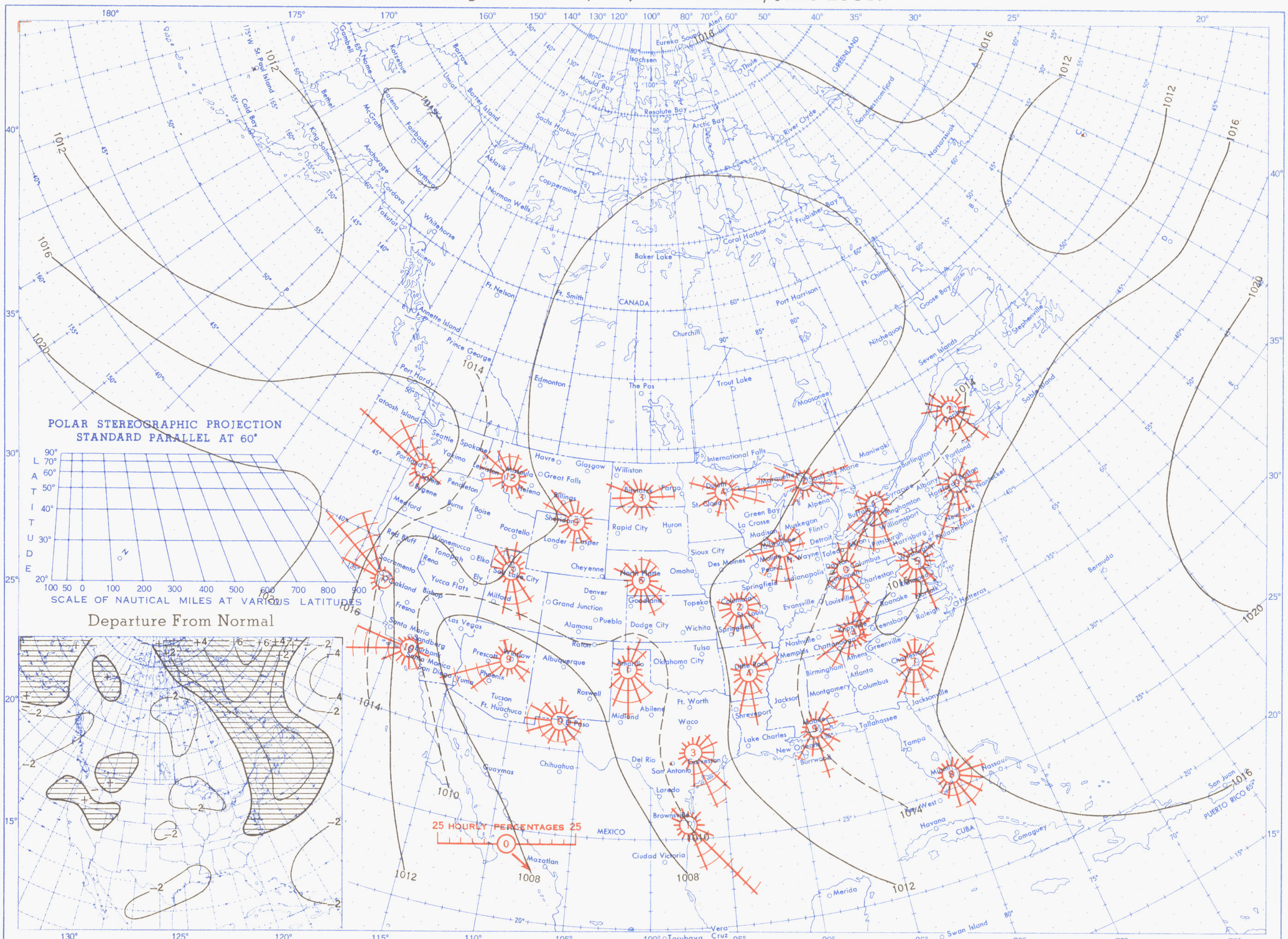
Circle indicates position of center at 7:00 a.m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, June 1957.



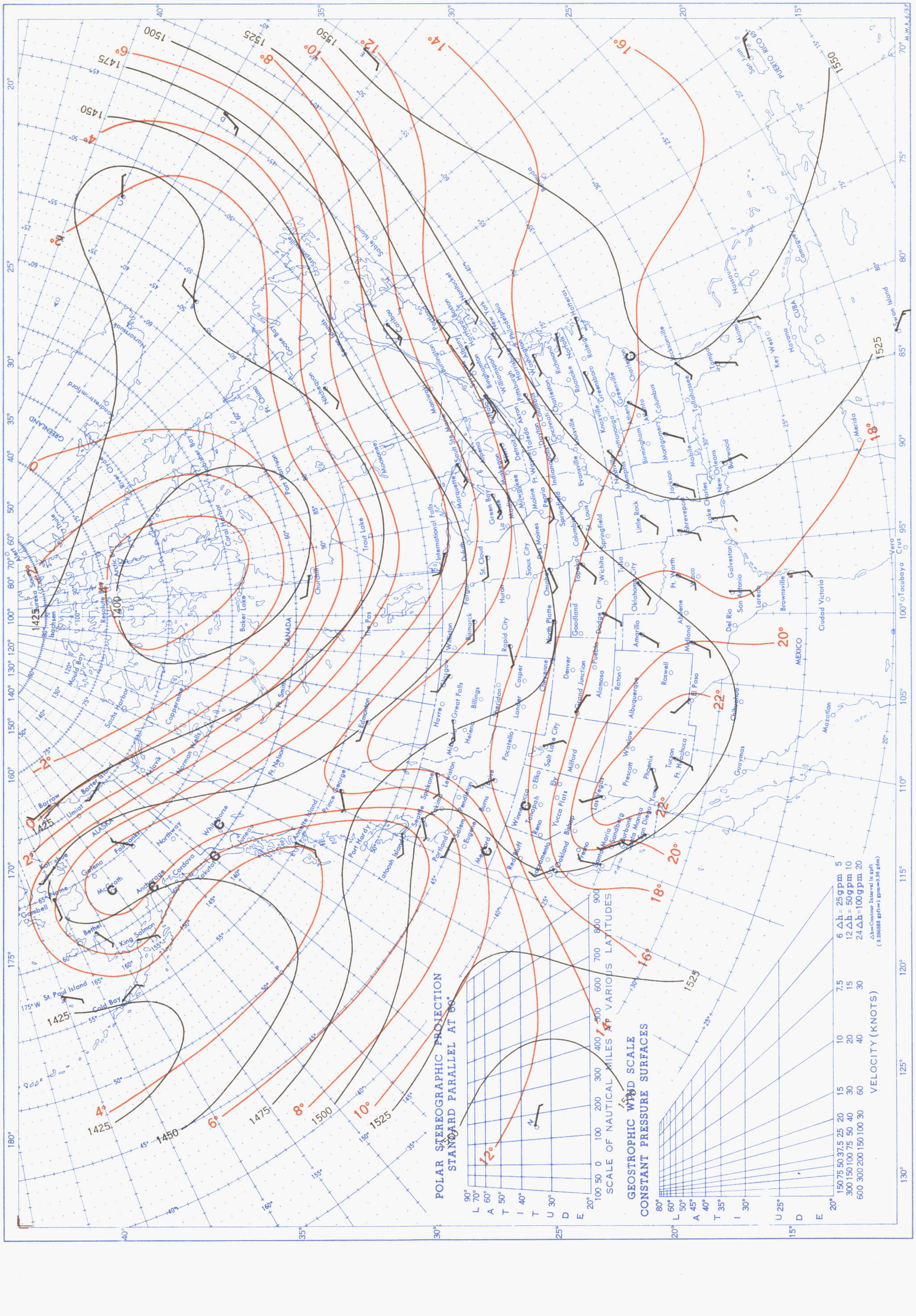
Circle indicates position of center at 7:00 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, June 1957. Inset: Departure of Average Pressure (mb.) from Normal, June 1957.



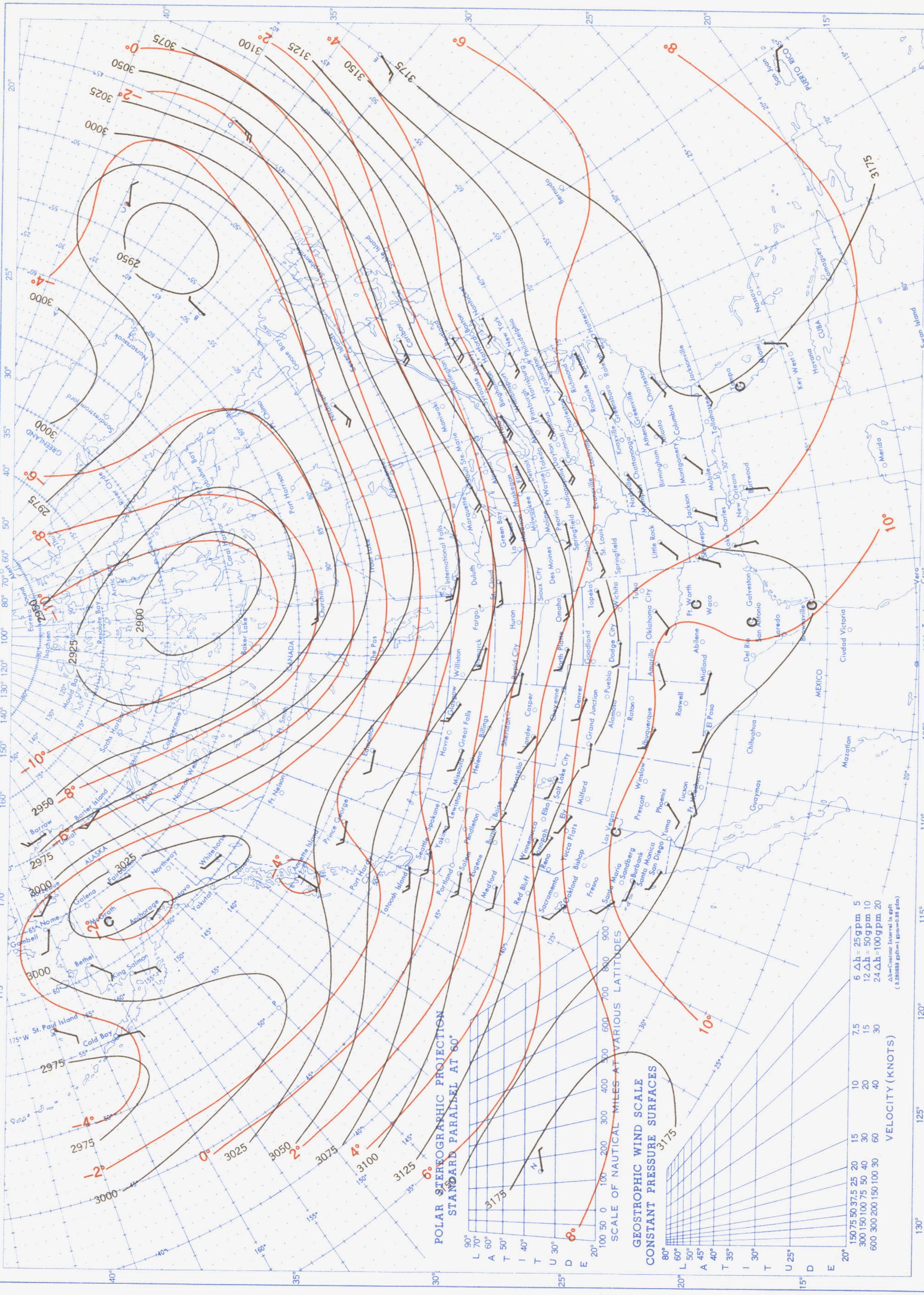
Average sea level pressures are obtained from the averages of the 7:00 a.m. and 7:00 p.m. E.S.T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. 850-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



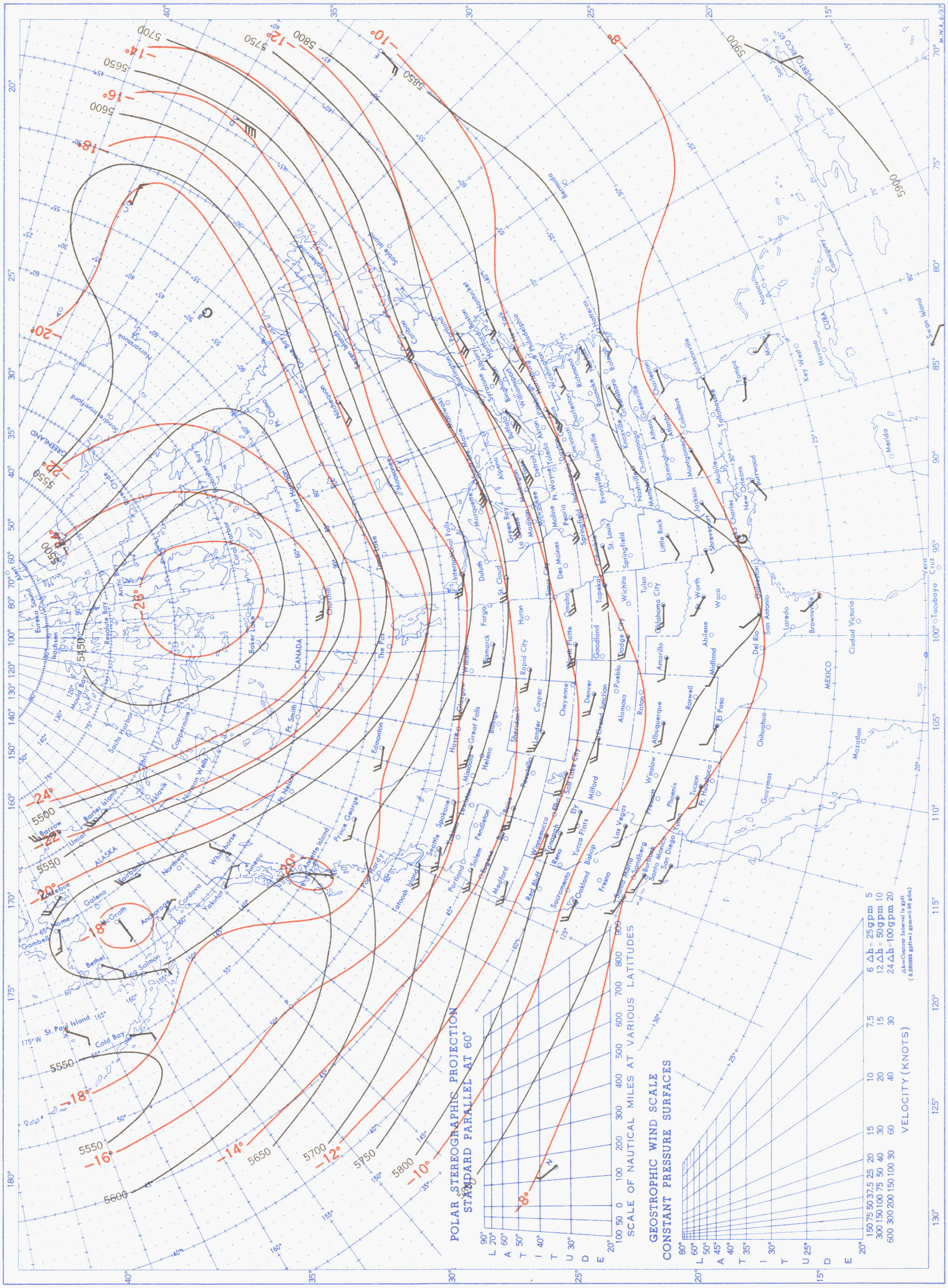
Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. All wind data are based on rawin observations.

Chart XIII. 700-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



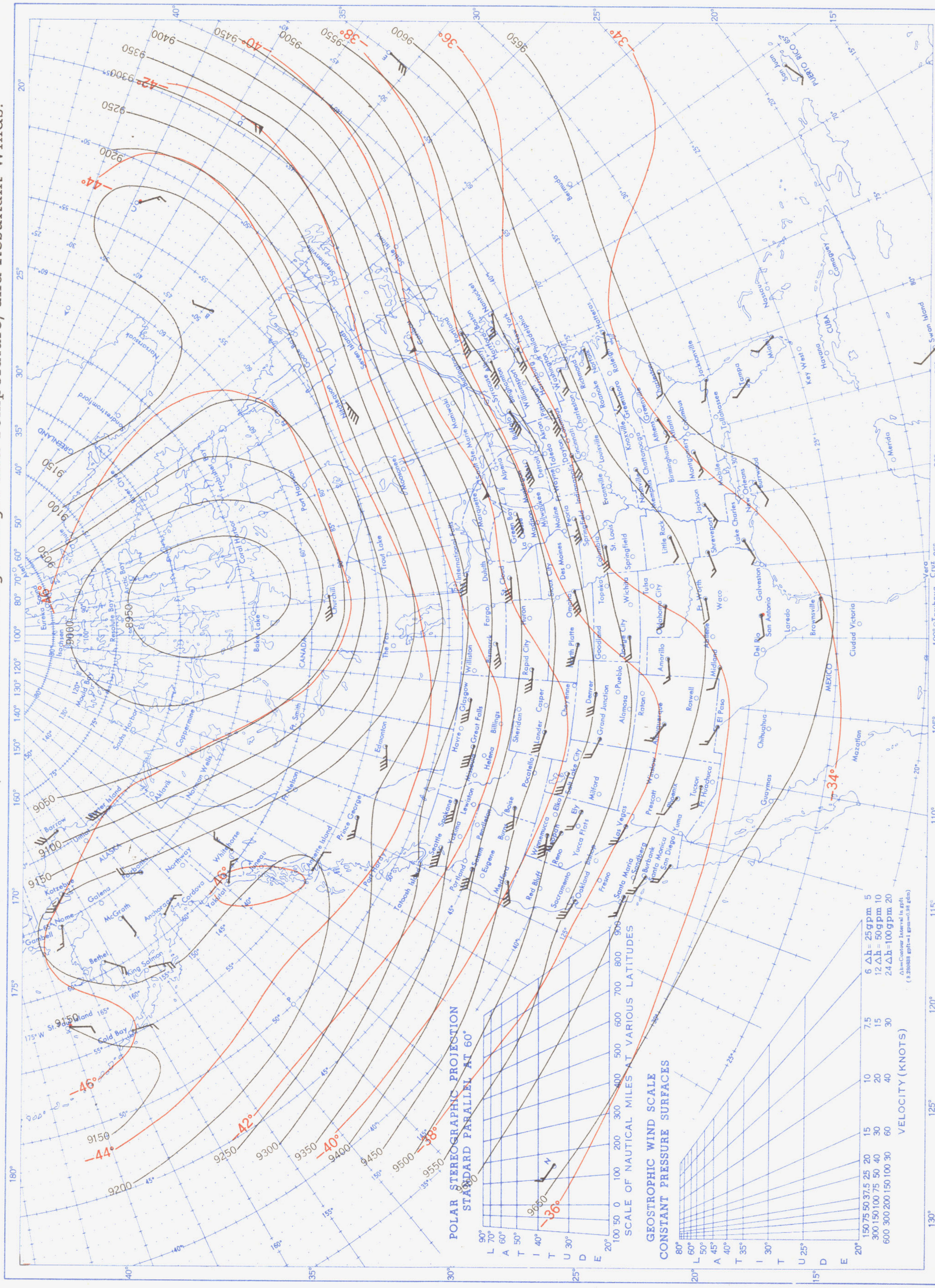
See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



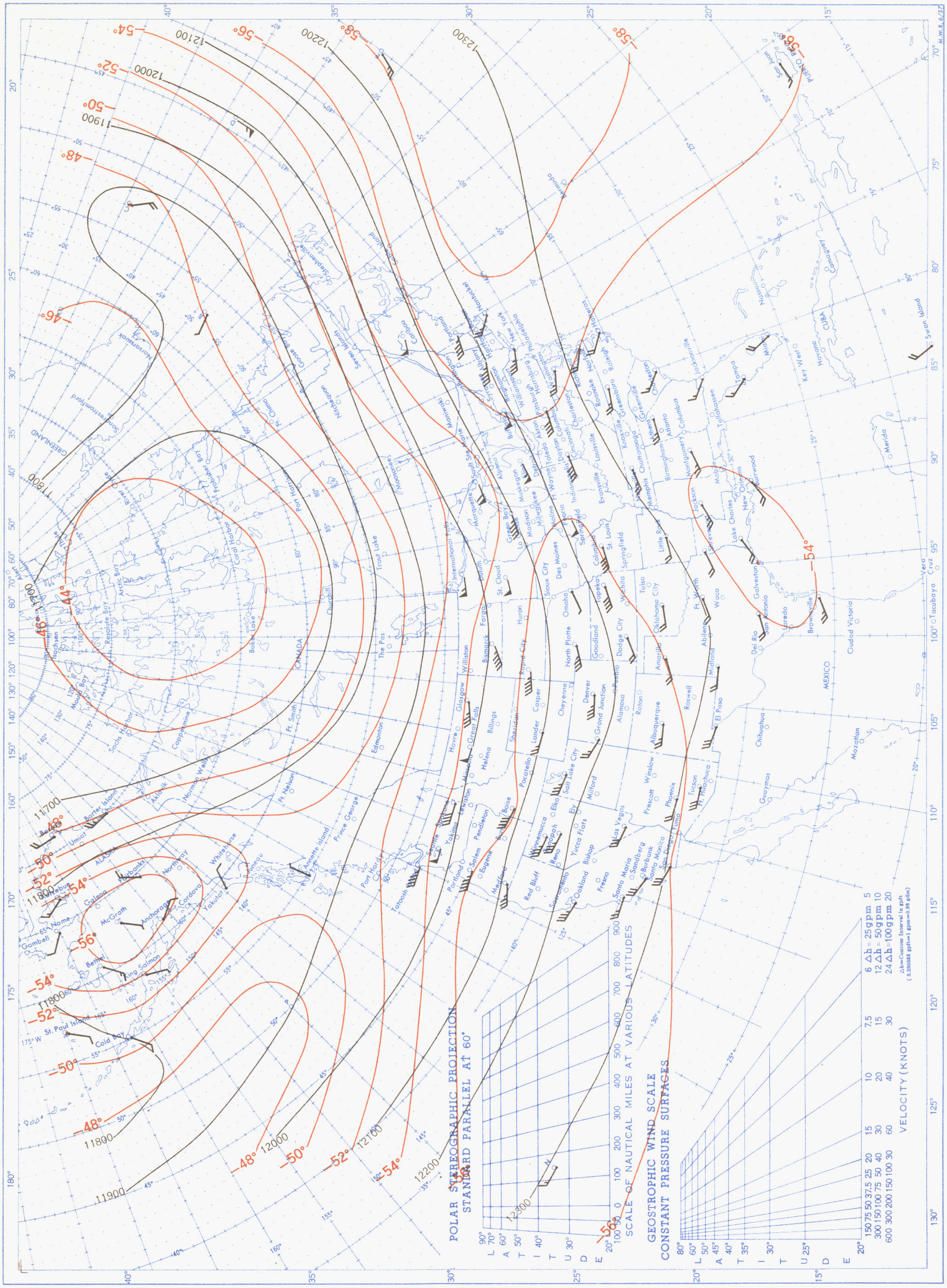
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



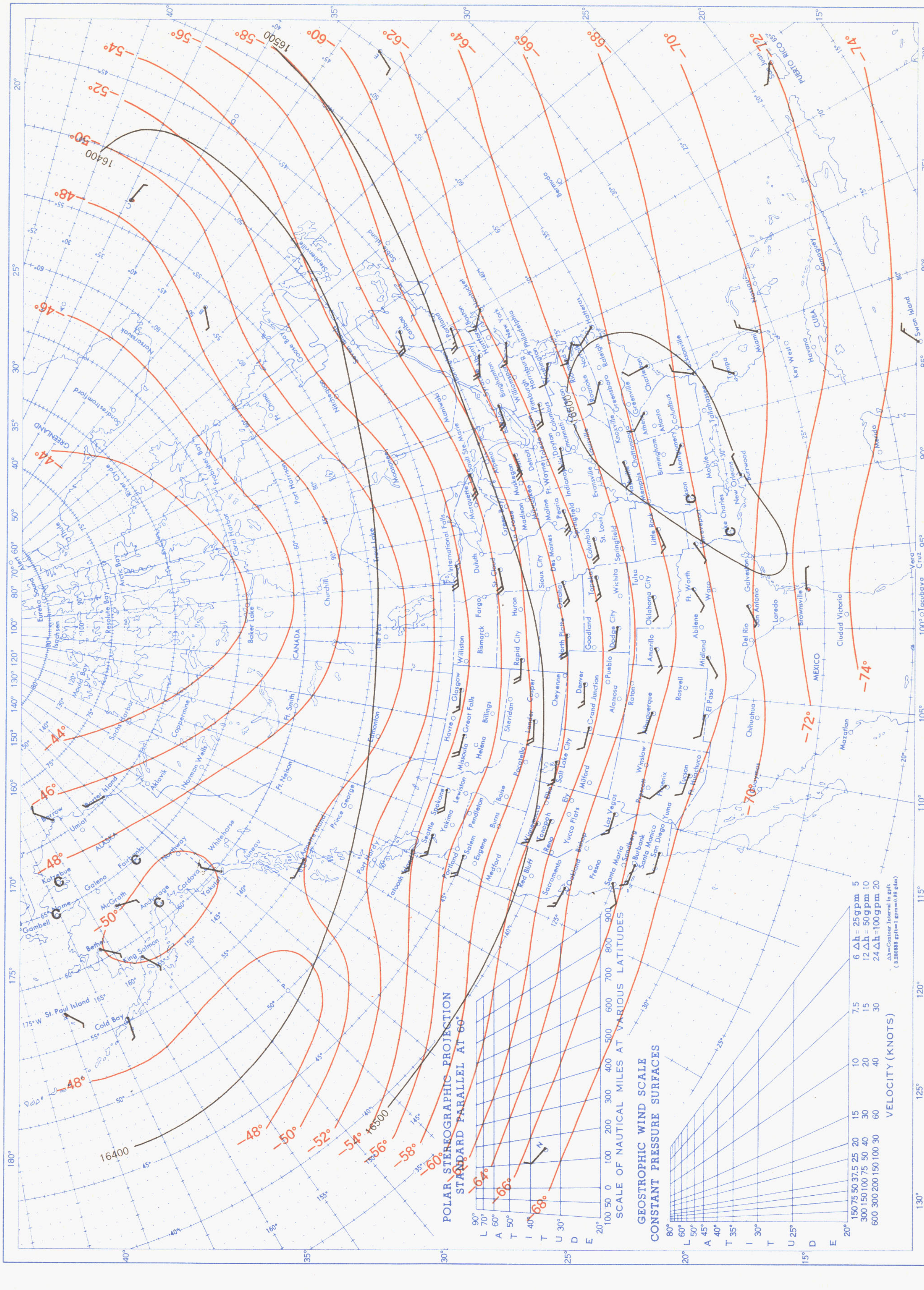
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.

Chart XVII. 100-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.